

CRANFIELD UNIVERSITY

ABDULLAH NASER ALKHALEDI

RENEWABLE ENERGY ENHANCED COMBINED CYCLE FOR LH2
CARRIER SHIP

PhD

Academic Year: 2021 - 2022

Supervisor: Professor Pericles Pilidis
Associate Supervisor: Dr. Suresh Sampath
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degree of PhD

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ABSTRACT

Achieving global climate change mitigation targets requires serious solutions to the global energy sources decarbonisation. Hydrogen as a clean alternative fuel represents a successful and viable option to achieve the future zero-carbon target, and it is considered a leading contender as a fuel for the future economy, and it is anticipated that there will be a strong demand for vessels capable of transporting liquefied hydrogen from the production to the consumption sites. However, the seaborne transportation of hydrogen represents a significant gap in the hydrogen supply chain; this leads to the following philosophical question: what would the hydrogen carrier ship look like? The novel contributions of this study are to present a design and evaluation for a liquefied hydrogen (LH₂) tanker fuelled by hydrogen named JAMILA in support of decarbonisation, storage and transportation of liquefied hydrogen with a total capacity of ~280,000 m³ as a cargo and uses the boil-off gas for propulsion for the loaded leg of the journey. A hydrogen-fuelled combined-cycle gas turbine was modelled and examined as a ship prim-mover to achieve the twin objectives of high efficiency and zero-carbon footprint. Also, the study presents an economic analysis of a liquefied hydrogen tanker, to determine the viability of using such ships to transport hydrogen in the future to contribute toward implementing a green hydrogen economy. In terms of operation, the LH₂ tanker was simulated for different journeys under various conditions to assess the ship's performance in terms of efficiency and environmental aspects. Moreover, the design was developed by implementing a set of 6 Flettner rotors for the JAMILA ship to achieve the fuel-saving and emission reduction targets. Established methods were employed using state-of-the-art design and analysis for determining the LH₂ tank sizing, ship hull design, ship stability, and ship characteristics. Additionally, the ship propulsion system was designed and evaluated based on the ship resistance requirements in off-design and degraded performance of the gas-turbine topping cycle. Moreover, a techno-economic and environmental risk assessment (TERA) method were developed to evaluate the suggested design in different conditions such as loaded and unloaded conditions, a normal and 6% degraded engine, and various weather conditions in different scenarios. The results indicated that the LH₂ tanker could carry 20,000 tonnes of liquefied hydrogen in a fully loaded with a displacement tonnage of 232,000 tonnes, and the design has been shown to be stable. The liquid hydrogen boil-off is

supplied to the ship's main engine, thereby saving 29% of the liquefied hydrogen fuel consumption of the ship in the fully loaded condition. Its propulsion system contains a combined-cycle gas turbine of approximately 50 MW. The results reveal that the output power allows ship operation at a great speed even with a degraded engine and adverse ambient conditions. However, implementing 6 Flettner rotors for the LH₂ tanker ship impacts the performance and leads to environmental benefits. A maximum contribution power of around 1.8 MW was achieved, saving approximately 3.6% of the combined-cycle gas turbine total output power (50 MW) and causing a 3.5% reduction in NO_x emissions. Economically, the results indicate that the JAMILA ship's implementation can cover the ship's capital cost within no more than 2.5 and 6 years in the best and worst-case maritime shipping prices conditions, respectively. The economic assessment results indicate a promising perception of the future development of sustainable energy systems and provide new information that is important for bridging the gap between research, development, and implementation of a green hydrogen economy that will contribute to mitigating climate change. Investments in ships such as the vessel designed and evaluated in this study represent an essential constituent of the decarbonisation process and could be one of the solutions to achieving almost the zero-emissions target in the future. This study definitively answers the question regarding the hydrogen tankers design and assessments.

Keywords:

Liquefied hydrogen; LH₂ tanker; Ship design; Liquid hydrogen tank; Propulsion system; Hydrogen economy; Economic; Green economy; Engine thermal efficiency; Combined-cycle gas turbine; NO_x emissions; Hydrogen-fuelled engine; LH₂ tanker mission; Renewable energy; LH₂ tanker Performance; Flettner rotors; Environmental

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1 INTRODUCTION

Extreme decarbonisation is a target for 2050, but there is a strong consensus that this is difficult to achieve under utilising the current unclean technologies and fuels. In 2015 in Paris, the world leaders signed an agreement to limit global warming by taking practical actions to limit the global temperature increase in order not to exceed 2 degrees Celsius [1]. On the same pathway, in 2021, the United Kingdom government hosted the 26th United Nations Climate Change Conference of the Parties (COP 26) to take action to achieve the Paris agreement and the United Nations Framework Convention on mitigation of Climate Change [2]. In order to achieve the climate change tackle goals, the world governments need to take several appropriate decarbonisation actions, such as creating zero-emission technologies and utilising alternative clean fuels. Hydrogen represents a viable option for decarbonising and significantly reaching the global climate change mitigation target [3]. Therefore, several countries planned large-scale hydrogen projects to be hydrogen supplier hubs leaders in the future [4]. Correspondingly, Hydrogen production, storage, transportation, and safety represent a significant challenge for the acceleration of marketing and utilising hydrogen worldwide [5]. In this regard, there is a need to focus on finding sustainable solutions to overcome the hydrogen economy challenges. The expectation indicated that most of the hydrogen production hubs would be located at the seaside to produce the hydrogen from the seawater using the electrolysis method. In terms of hydrogen transportation, the production hubs will need a large number of seaborne tankers to carry the hydrogen from the supplier's hubs to the demander ports. The design and evaluation of large-scale liquefied hydrogen tankers could be one of the practical solutions to achieving hydrogen utilisation and economic targets.

Moreover, In July 2019, the United Kingdom department of transport published the UK Clean Maritime Plan to serve as an environmental road map to achieve the government's Maritime 2050 vision, intended to transition shipping in UK waters to a zero-emissions future with the requirement that by 2025, all new vessels in UK waters be designed with zero-emissions power capabilities. Clearly, extant traditional marine power technology will be unable to meet these targets, particularly zero-emissions targets. However, using hydrogen and renewable energy for the vessels' propulsion systems as a clean

alternative could be a successful option to achieve the maritime almost zero-emission target [6].

This research project's contributions include a new design and assessment of a liquefied hydrogen tanker propelled by a hydrogen-fuelled combined cycle gas turbine alone and assisted with 6 Flettner rotors as a renewable energy technology to give a preliminary answer to the unusual philosophical question; What could a hydrogen tanker look like? Furthermore, establishing a novel framework to evaluate techno-economic environmental risk assessment (TERA) for power, efficiency performance, shipping emissions, and long-term investment of liquified hydrogen carrier ship powered by combined cycle gas turbine hydrogen-fuelled enhanced with Flettner rotor to meet the almost zero-emission target with efficient ship propulsion and power system.

1.1 Goal and Motivation

A novel design of a large hydrogen carrier ship to achieve almost a zero-emission target for the global.

1.2 Aim

Design and techno-economic environmental risk assessment (TERA) evaluation of combined Brayton and Rankine cycles along with wind energy for liquified hydrogen carrier ship through numerical modelling for a novel marine propulsion and power system working towards the future of zero-emission target.

1.3 Objectives

1. Identify the current propulsion and power technology for merchant marine applications, alternatives, evaluations, and global shipping emissions produced.
2. Adapt a method to design the liquified hydrogen carrier ship and evaluate the power system's performance presented by overall thermal efficiency and power output in design and off-design ambient conditions.
3. Design and evaluate the hydrogen tanker hull, isolated LH2 tanks, and stability analysis in fully cargo loaded and unloaded conditions (baseline scenario).

4. Model and examine COGAS power system with a turboelectric azimuthal podded drive system as a hydrogen tanker primary propulsion system (baseline scenario).
5. Model a systematic economic aspect presented by the Net present value (NPV), Internal rate of return (IRR), Pay back period (PP), and Economic added value (EAV) for the hydrogen carrier ship in the long and short term for an actual-life use of the LH2 carrier ship (baseline scenario).
6. Develop and simulate a numerical model for liquified hydrogen carrier ship powered by COGAS into the marine gas turbine application using the performance tool "Poseidon" (assess lifecycle and reliability in different journeys and conditions for the baseline scenario).
7. Model and preliminary design of Flettner rotor technology to be integrated into the designed hydrogen carrier ship as a wind-assisted scenario.
8. Develop a techno-environmental analysis method to assess the designed hydrogen-tanker ship in conjunction with 6 Flettner rotors in design and off-design conditions in terms of the performance and environmental impacts (wind-assisted scenario).
9. Simulate the 6 Flettner rotors with a designed liquified hydrogen carrier ship powered by COGAS in different journeys and conditions, compare the wind-assisted scenario results with the baseline, and verify the results with authentic published data (wind-assisted scenario).

1.4 Gap of Knowledge

Simultaneously ensuring sustainability, reducing environmental pollution, and providing high-quality energy production is a significant challenge for the global to achieve the future emission reduction target. This led to the intensification of the research in new designs of clean technologies and the evaluation of alternative fuel types to achieve the global reduction emission target. However, to the best of the researcher's knowledge, there has been no research on designing and evaluating the large scale of hydrogen tankers and integrating Flettner rotors with a hydrogen-fuelled combined gas and steam cycle power plant (COGAS) for a hydrogen carrier vessel propulsion and power generation. Therefore, this research will fill the following gaps:

- Design and model a novel large-scale hydrogen carrier and fuelled ship, including a cylindrical tank with hemispherical endcaps, isolated LH2 tanks, ship stability in loading and unloading conditions, and a COGAS propulsion system.
- Evaluate techno-economic environmental risk assessment (TERA) for COGAS hydrogen carrier ship efficiency, performance, emissions, and long-term investment.
- Produce large-scale liquefied hydrogen carrier ship design, taking advantage of Flettner rotor technology in clean hydrogen as assistance propulsion systems.
- Analyse the integration of Flettner rotor technology enhanced with COGAS as a sustainable, comprehensive propulsion system for liquified hydrogen carrier ship in terms of performance and environmental aspects.

1.5 Contribution to Knowledge

The research project contributes a novel hydrogen tanker design, including a propulsion system, which will be developed by integrating renewable energy technology with COGAS fuelled by hydrogen, working towards the future zero-emission target.

1.6 Overall Research Methodology

This section aims to describe the overall research methodology to design and evaluate the liquefied hydrogen carrier ship powered by a combined cycle gas turbine (COGAS) fuelled by hydrogen as a ship prim mover in conjunction with Flettner rotors technology as an assistance propulsion system to achieve the fuel-saving and emission reduction targets. This design was performed and evaluated using "TURBOMATCH," "MATLAB," "MAXSURF," "Rhino 6", and SOLIDWORKS software to simulate the liquified hydrogen carrier ship design within a ship-wide "Poseidon" simulation tool. Such an approach evaluates proposed systems using models for their thermodynamic, economic, and environmental performance. Two scenarios for the liquefied hydrogen tanker operational were simulated: Liquefied hydrogen tanker powered by combined cycle gas turbine only as a baseline scenario and in conjunction with Flettner rotors technology as a wind-assisted scenario. Both scenarios accounted for off-design requirements from geographic location and ambient conditions for liquified hydrogen

carrier ships in different journeys. Furthermore, the analysis also provided a techno-economic, environmental, and risk assessment, as this is a suitable method for evaluating the ability of a proposed liquified hydrogen carrier ship to meet the zero-emission target with an efficient ship power system.

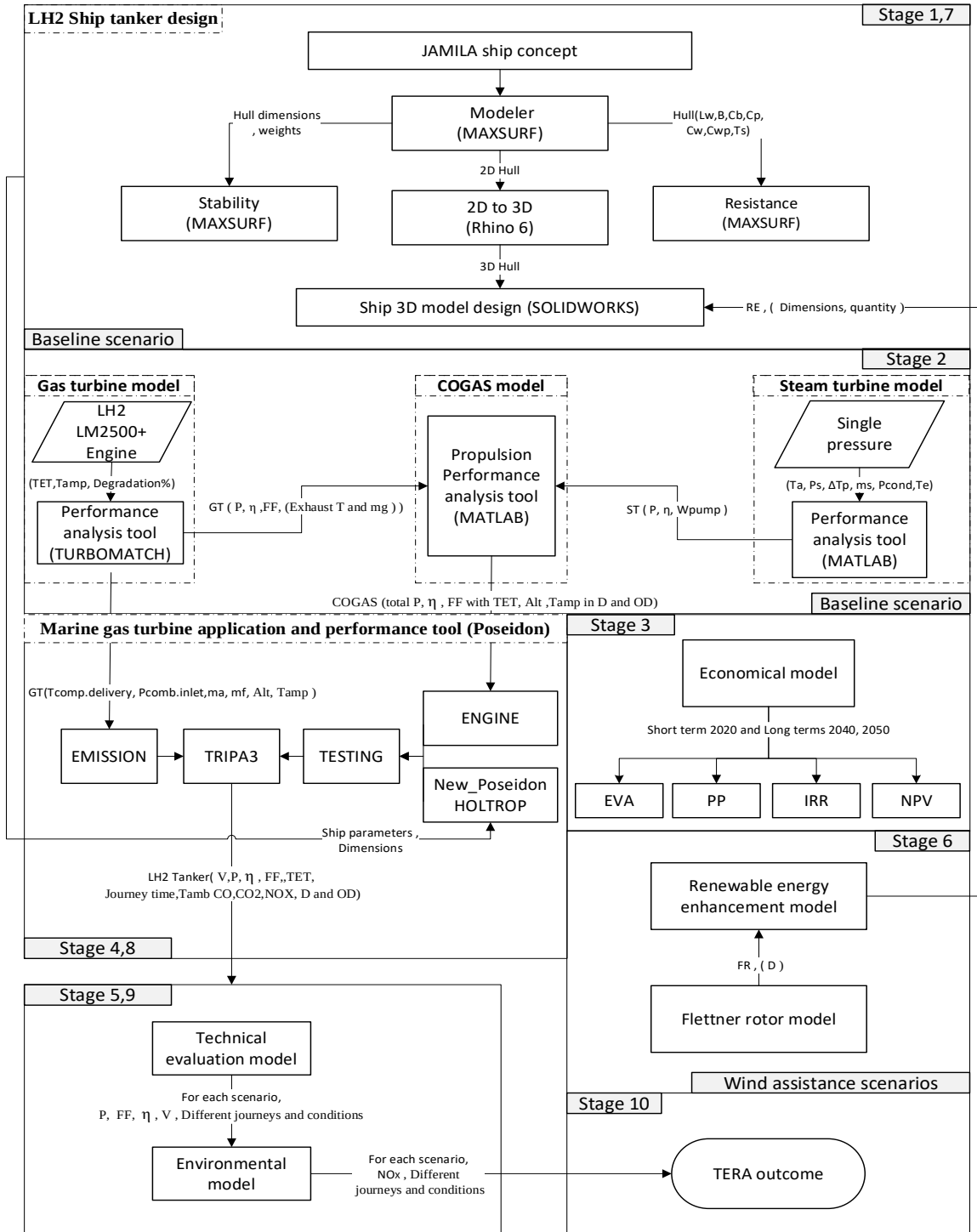


Figure 1-1 Research overall methodology flow chart

The overall research methodology in this research is divided into ten stages, as shown in Figure 1-1. These stages can be explained as follows:

Stage 1

Design the liquefied hydrogen carrier ship, considering the hydrogen properties (very light but voluminous), liquid hydrogen tanks mechanical and thermal sizing, ship hull dimensions and weights, ship stability, ship resistance and required power, and create ship 3-dimension design. (The tools used in this stage are: MAXSURF Modeler, MAXSURF Stability, MAXSURF Resistance, Rhino 6, and SOLIDWORKS).

Stage 2

Model and examine combined cycle gas turbine via integrating the LM2500+ gas turbine engine and a single pressure non-reheated steam turbine engine using a heat recovery steam generator. Technically, the mathematical model of a combined cycle gas turbine is based on different thermodynamic assumption parameters to evaluate the performance of a combined cycle gas turbine by calculating output power, thermal efficiency, and hydrogen fuel flow influence of turbine inlet temperature in a range of (1370:30:1680K), the ambient temperature in the range of (-20:15:35C), and degradation of 2,4,6%. (The tools used in this stage are: TURBOMATCH / MATLAB).

Stage 3

Develop an economic assessment method to evaluate the economic feasibility of the liquefied hydrogen tanker to determine the ship's net present value (NPV), internal rate of return (IRR), payback period (PP), and economic value added (EVA). In this stage, a systemic economic analysis was implemented based on the Business Model Canvas (BMC) as an effective strategic management tool to assess the liquefied hydrogen tanker through three different scenarios; In the first scenario, 'short-term 2020', the hydrogen price and the hydrogen shipping price assumed as USD\$6/kg and USD\$1.2/kg respectively. The second scenario is 'long-term 2040', wherein the fuel price will decrease to USD\$2/kg, and the shipping cost will be the same as that in the short-term 2020 scenario. Finally, the third scenario, 'long-term 2050', assumes that the hydrogen cost will decrease to USD\$2/kg and the cargo shipping cost will decrease to USD\$0.7/kg.

Stage 4

Implement the combined cycle model and the liquefied hydrogen carrier ship design in the numerical "Poseidon" tool to simulate the liquefied hydrogen carrier ship powered by a combined cycle gas turbine hydrogen-fuelled for different journeys (Tangier to Southampton- Algeria to Marseille) and different conditions as a baseline scenario. Poseidon tool contains five routines the engine performance model (ENGINE) used to simulate the combined cycle gas turbine model with the influence of turbine inlet temperature assumed to range between (1025:25:1700 K), ambient temperature range (-25:10:45C), an altitude of (-200:0:200). The second is the marine vessel power prediction (New Poseidon HOLTROP) to simulate the ship's total resistance and brake power required. The third is the power plant management model (TESTING) is used as a function to connect between (New Poseidon HOLTROP) and (ENGINE). The fourth is the emission management model (Emission) to calculate emissions in different conditions using the gas turbine model outputs. The last model is a trip management model (TRIPA3) used to integrate the four previous functions and generate the output of the liquified hydrogen carrier ship simulation results. (The tool used in this stage is: the Poseidon tool).

Stage 5

Construct a techno-environmental model to simulate the liquefied hydrogen carrier ship powered by combined cycle gas turbine technology alone as a baseline scenario by calculating the total power output, thermal efficiency, fuel flow and output Nitrogen Oxides emissions (NOx) for liquefied hydrogen carrier ship prime mover. The techno-environmental assessment was analysed on different journeys (Tangier to Southampton- Algeria to Marseille) and under different conditions; ambient temperature with the range of -25:10:45C and degradation of 6% for off-design evaluation. (The tool used in this stage is: the Poseidon tool).

Stage 6

Design the renewable energy enhancement model using a Flettner rotor model, taking into account the Flettner rotors number, size, weight and the distance between each

Flettner rotor to be suitable with the ship dimensions to achieve the optimum output power from the wind energy.

Stage 7

Design a 6 Flettner rotors in conjunction with the combined cycle gas turbine model as an assistance propulsion system for the liquefied hydrogen carrier ship (The tool used in this stage is: SOLIDWORKS).

Stage 8

Simulate the integration of the Flettner rotor model with a combined cycle gas turbine as a novel propulsion system for liquefied hydrogen carrier ship in the numerical "Poseidon" tool as a wind-assisted scenario. (The tool used in this stage is: Poseidon).

Stage 9

Evaluate the Flettner rotors model in conjunction with liquefied hydrogen carrier ship powered by a combined cycle gas turbine using techno-environmental assessment models in different journeys (Tangier to Southampton- Algeria to Marseille) and conditions; ambient temperature of -25:10:45C and degradation of 6% for off-design evaluation. (The tool used in this stage is: the Poseidon tool).

Stage 10

Extract and compare the evaluation results for the liquefied hydrogen carrier ship powered by a combined cycle gas turbine alone and in conjunction with Flettner rotors technology by applying the Techno-Economic Environmental Risk Assessment (TERA) method as a framework.

1.7 List of Published and Submitted Papers

The work conducted for this research has revealed a novel design and assessment of a liquefied hydrogen tanker through five original scientific research manuscripts can be presented in table 1-1:

Table 1-1 A description of published and submitted papers

Chapter	Paper	Objective	Title and journal	Status
2	1	1,2,3	Abdullah NFNR Alkhaledi, Suresh Sampath & Pericles Pilidis (2021) A hydrogen fuelled LH2 tanker ship design, Ships and Offshore Structures, DOI: 10.1080/17445302.2021.1935626.	Published (Taylor & Francis) Impact factor 1.99
3	2	1,2,4	Alkhaledi ANFNR, Suresh Sampath & Pericles Pilidis (2022), Propulsion of a hydrogen-fuelled LH2 tanker ship, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.03.224 .	Published (ELSEVIER) Impact factor 5.81
4	3	1,5	Abdullah NFNR Alkhaledi, Suresh Sampath & Pericles Pilidis (2022), " Economic Analysis of a Zero-Carbon Liquefied Hydrogen Tanker Ship", International Journal of Hydrogen Energy.	Published (ELSEVIER) Impact factor 5.81
5	4	1,6,8	Abdullah NFNR Alkhaledi, Suresh Sampath & Pericles Pilidis (2022), " Techno-Environmental Assessment of COGAS-Fuelled by Hydrogen for LH2 Tanker Ship ", Energy Reports.	Under Review (ELSEVIER) Impact factor 6.87
6	5	1,7,8,9	Abdullah NFNR Alkhaledi, Suresh Sampath & Pericles Pilidis (2022), " Techno Environmental Assessment of Flettner Rotor as an assistance propulsion system for LH2 Tanker Ship fuelled by hydrogen ", Renewable & Sustainable Energy Reviews.	About To be Submitted

1.8 Thesis Structure

The thesis consists of five connected self-contained papers enhanced with an overall discussion and conclusion chapter. Additionally, appendices as supplementary material also will be presented in the thesis. The thesis structure concise description is presented as follows.

Chapter 2: Paper 1 - A Hydrogen Fuelled LH₂ Tanker Ship Design

Overview: This chapter provides a philosophical view and evaluation of a comprehensive preliminary design of a large 370 m length ship, 75 m breadth, and 10.12 m draft to carry 20,000 tons of liquefied Hydrogen.

Chapter 3: Paper 2 - Propulsion of a Hydrogen-Fuelled LH₂ Tanker Ship

Overview: This chapter provided a perspective of a propulsion system for a large-scale hydrogen-fuelled liquid-hydrogen (LH₂) tanker ship. The ship propulsion system was evaluated in off-design conditions based on the ship resistance requirements, and a 50 MW hydrogen-fuelled combined-cycle gas turbine was modelled to achieve the twin objectives of high efficiency and zero-carbon footprint for satisfying global objectives toward climate change tackle.

Chapter 4: Paper 3 - Economic Analysis of a Zero-Carbon Liquefied Hydrogen Tanker Ship

Overview: This chapter presents an economic assessment of the designed liquefied hydrogen tanker to establish the feasibility of using such ships to transport hydrogen in the future to contribute to implementing a green hydrogen economy.

Chapter 5: Paper 4 - Techno-Environmental Assessment of a Hydrogen-Fuelled Combined-Cycle Gas Turbine for a Liquid Hydrogen Tanker

Overview: This chapter aimed to improve the design and conduct a techno-environmental analysis for the designed liquid hydrogen (LH₂) tanker powered by a hydrogen-fuelled combined-cycle gas turbine (COGAS) only as a prime mover in different journeys and conditions.

Chapter 6: Paper 5 - Techno Environmental Assessment of Flettner Rotor as assistance propulsion system for LH2 Tanker Ship fuelled by hydrogen

Overview: This chapter presented a novel and developed design of a liquefied hydrogen tanker ship by implementing a set of 6 Flettner rotors as an assistance propulsion system in conjunction with a combined-cycle gas turbine fuelled by hydrogen as a prime mover and assessment of this design in terms of the technical and environmental aspects to analyse the influence of the renewable energy technology in the ship prime mover in different journeys and conditions.

Chapter 7: Overall Discussion

Overview: This chapter represents the implementation of the work by linking the findings from the five original research papers to deliver the overall aim of the research.

Chapter 8: Conclusion

Overview: This chapter is dedicated to the conclusion of the main results of the research.

Chapter 9: Further work

Overview: This chapter presents future work to develop the research and implement the new ideas and technologies in the future.

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2 PAPER 1 - A HYDROGEN FUELLED LH2 TANKER SHIP DESIGN

Abdullah NFNR Alkhaledi*, Suresh Sampath, and Pericles Pilidis

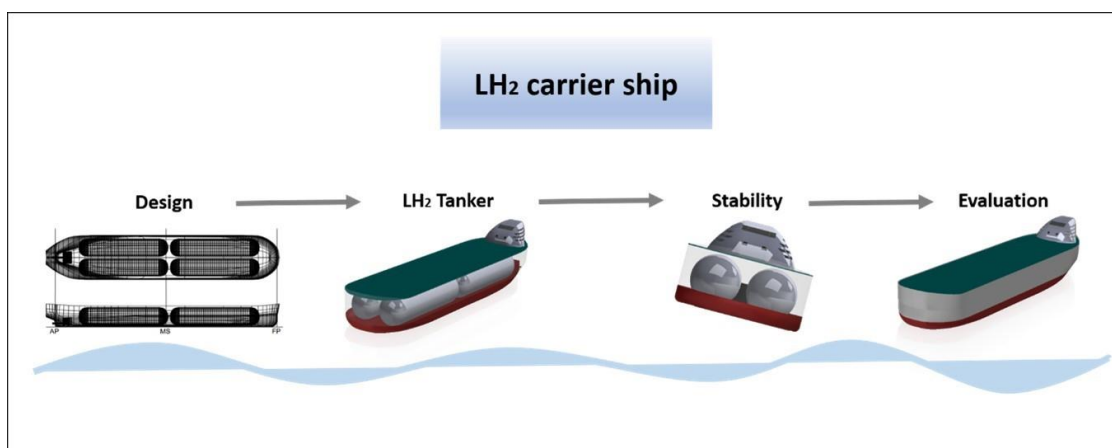
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Abstract

This study provides a detailed philosophical view and evaluation of a viable design for a large liquid hydrogen tanker fuelled by liquid hydrogen. Established methods for determining tank sizing, ship stability, and ship characteristics were used to evaluate the preliminary design and performance of the liquefied hydrogen tanker named ‘JAMILA’, designed specifically to transport liquid hydrogen. JAMILA is designed around four large liquid hydrogen tanks with a total capacity of $\sim 280,000 \text{ m}^3$ and uses the boil-off gas for propulsion for the loaded leg of the journey. The ship is 370 m long, 75 m wide, and draws 10.012 m at full load. It has a fully loaded displacement tonnage of 232,000 tonnes to carry 20,000 tonnes of hydrogen. Its propulsion system contains a combined-cycle gas turbine of approximately 50 MW. The volume of the hydrogen cargo pressurised to 0.5 MPa primarily determines the size and displacement of the ship.

Graphical Abstract:



Keywords: Liquefied hydrogen; LH₂ tanker; Ship design; Liquid hydrogen tank

Nomenclature

Symbol	Meaning	Symbol	Meaning
B	Extreme ship breadth	MTC^1	Moment required to change trim by 1 cm
Bv	Volumetric thermal expansion coefficient	N_{UD}	Nusselt number
$BM_{T,L}$	Transverse, longitudinal metacentric radius of the ship	P_{LH2}	Pressure inside the tank
C_B	Block coefficient	PR	Prandtl number
C_m	Midship section area coefficient	$Q_{convection}$	Heat convection
C_p	Prismatic coefficient	$Q_{in \text{ to the tank}}$	Tank heat input
C_{wp}	Waterplane area coefficient	$Q_{out \text{ of the tank}}$	Tank heat output
D	Ship depth	$Q_{radiation}$	Heat radiation
DWT	Deadweight	r	Internal tank radius
FOS	Factor of safety	R_{ad}	Rayleigh number
G	Gravitational acceleration	R_1	Inner insulation radius
GM	Metacentric height	R_2	Outer insulation radius
$GM_{T,L}$	Transverse, longitudinal metacentric height	T_{in}	Temperature inside the tank
GZ	Righting arm	T	Ship draft
H	Convection coefficient for air surrounding the tank	$t_{insulation}$	Insulation thickness
h_{fg}	Latent heat of vaporisation of liquid hydrogen	T_{LH2}	Internal tank temperature
I_T	Transverse moment of inertia	$T_{surface}$	Insulation surface temperature
K	Insulation thermal conductivity	t_w	Wall thickness for the cylindrical tank
K_g	Air thermal conductivity	T_{∞}	Temperature transitions from the external temperature
KB	Vertical centre of buoyancy	TPC	Tonnes per centimetre immersion
KG	Vertical centre of gravity	V_i	Excess volume
$KM_{T,L}$	Transverse, longitudinal height of the metacentre above the keel line	V_t	Total tank volume
L	Tank cylinder section length	VCG	Vertical centre of gravity
L_{total}, L_{et}	Tank total hemisphere and cylinder sections internal and external length	Δ_{total}	Ship total displacement
LBP	Length between forward and aft perpendicular	ϵ	Emissivity of the insulation surface
LCB	Longitudinal centre of gravity	ρ_{insu}	Density of the rigid open-cell polyurethane
LCF	Longitudinal centre of floating	ρ_{LH2}	LH ₂ density
LH_2	Liquefied hydrogen	ρ_{liner}	Aluminium alloy liner (Al-Mg 5086) density
LHV	Lower heating value	ρ_t	Aluminium density (4.4% Cu)
LNG	Liquefied natural gas	σ	Stefan–Boltzmann constant
LOA	Length overall	σ_y	Yield strength of aluminium (4.4% Cu)
LW	Length of waterline		
LWT	Lightweight		
$M_{boil \text{ off}}$	Mass of hydrogen boil off		
$M_{insulation}$	Mass tank of insulation		
M_{LH2}	Mass of liquefied hydrogen		
M_{liner}	Mass of tank liner		
$\sum_{momentl}$	Total moment of the keel		
M_t	Mass of the hydrogen tank before being isolated		
$M_{total \text{ LH2 tank}}$	Total mass of the hydrogen tank after being isolated		

2.1 Introduction

Intensive global efforts are currently focused on decarbonisation to achieve the EU 2050 net-zero emissions target (European Commission 2019). The utilisation of hydrogen has a high potential to be a viable option for decarbonisation in different sectors such as transportation, energy, manufacturing, and the residential and commercial sectors (Körner, A et al., 2015). There is enormous interest in the generation and utilisation of

hydrogen future technologies; for instance, the EU has specified that half the essential energy demand is fulfilled by hydrogen, i.e., 3100–6000 TWh/year of hydrogen, is assessed to be required by 2050 (European Commission 2019; van Wijk et al. 2020). Additionally, in 2025, the commissioning of the largest green hydrogen project by Neom is expected to save globally 3 million tons of CO₂ emissions each year by creating 650 tons of hydrogen each day, and henceforth, utilising an environmentally friendly power to achieve a sustainable hydrogen economy (Scita, R et al. 2020).

In this regard, the key issues that necessitate examination are hydrogen storage, transportation, and safety to enable the usability of hydrogen on a global scale. The use of hydrogen as an energy fuel is considered particularly useful in the context of electricity generation involving a significant mismatch between supply and demand. Besides, creating hydrogen from sustainable resources will be a remarkable alternative, wherein it will be possible to store power in the hydrogen structure of the resource from which it shall originate and revert it to utilisation when required. The employment of clean energy sources such as wind, solar, and nuclear energy to the seawater electrolysis process for hydrogen production indicates that coastal countries between the tropics appear promising sources of green hydrogen production. This will require the transportation of this green hydrogen to other places of high demand. As mentioned, the Neom project will generate approximately 5,20,000 Kilograms of liquefied hydrogen per day. This large quantity of liquefied hydrogen is expected to be exported to other countries via seaborne using liquefied hydrogen carrier ships, requiring an expected back and forth journey of 20 days. In terms of weight, liquefied hydrogen is approximately 800 times denser than gaseous hydrogen at atmospheric pressure (Scita, R et al. 2020; Escher and Ohta 1979). Thus, there is a need to construct more than 500 large-scale liquefied hydrogen carrier ships, each with an approximate capacity of 20,000 tons of liquefied hydrogen, within a decade, to operate this promising project. Therefore, there is a need to design large liquefied hydrogen tanker ships to support global hydrogen projects in the future.

There are limited previous studies with a similar background that can be found in the literature. In 1998, a group of Japanese companies published a preliminary study on large-scale transportation of liquid hydrogen, including a preliminary conceptual design

of a liquid hydrogen tanker with a prismatic and spherical four-tank system having a total capacity of 200,000 m³ and total cargo weight of 14,000 tons of liquefied hydrogen (Abe et al. 1998). Also, a design of an LNG carrier ship with different wedged tanks was introduced (Zhang 2015).

There is considerable potential for carbon-free hydrogen production using solar energy in regions with a marine coast that benefits from extensive sunshine, for example, North Africa and the Arabian Gulf. This will raise the demand to transport the hydrogen from the production sites to the consumption sites. However, other consumption centres will have a significant demand for hydrogen trade. In this regard, an effective method to transport hydrogen will be by the sea. Until recently, the integrated study of liquefied hydrogen tanker ship design and stability analysis have not been considered. This leads to the following question: what would a hydrogen tanker look like?

The objective of this study is to provide a preliminary answer to this design question. Using state-of-the-art design and analysis methods, the authors offer a practical view of the design of such a ship. This study does not include economic and costs analyses which will be carried out in a future study using the TERA assessment method specifically for different marine applications, which was introduced for comparable studies (Nalianda 2012; Tsoudis 2008; Talluri et al. 2016).

2.2 Overall Design Philosophy and Major Specification

The philosophical starting point for this evaluation was an existing LNG tanker design, also known as the Mozah (Noble 2009; Pratt et al. 2009; RINA 2007). Table 2-1 shows the characteristics of this ship. Liquefied hydrogen properties are shown in Table 2-2. Liquefied hydrogen can be obtained by cooling hydrogen to $-253\text{ }^{\circ}\text{C}$; this will give it a density of 70.79 kg/m³, much higher than 0.089 kg/m³ at $0\text{ }^{\circ}\text{C}$, also higher than 38 kg/m³ when stored at 70 MPa. (Colozza and Kohout 2002). So, the use of liquid hydrogen requires a much smaller volume and storage at a much lower pressure. Therefore, to reduce the physical size of the ship, the authors opted to design the ship to carry liquid hydrogen because the volume and pressure requirements are much smaller than those associated with the compressed hydrogen gas. This choice promises a smaller ship and a much lighter tank. There are several reasons for selecting four tanks, such as maintaining the ship balance during the journey, preparing piping factors and positions,

and preserving the stability in the event of damage. A large amount of liquefied hydrogen will produce 20 tonnes of hydrogen boil-off per day during the journey, considering 1.68 m as the thickness of the insulation tanks. The main engine of the ship will be supplied with liquefied hydrogen cargo boil-off in the same way as in the LNG ships. The boil-off amount will save 29% of the liquefied hydrogen fuel consumption of the ship in the fully loaded condition, where the total fuel consumption of the ship is 68.9 tonnes per day of hydrogen, and the power generation is assumed to be 50 MW using a combined gas and steam turbine propulsion system, based on the designed power of an LNG tanker ship. The tank is designed to fit inside the hull, which contains four tanks of liquefied hydrogen. The large volume of liquefied hydrogen, when compared with that of LNG, results in a ship of very large dimensions with respect to the weight of the cargo it carries. Furthermore, the light weight of the cargo results in a design with an unusually shallow draft for the size of the ship. The ship's propulsion and steering are delivered by two podded azimuthal systems. Finally, the ship stability and hydrostatic values were calculated and validated by using the IMO Intact Stability Code (ISC) (IMO 2008).

Table 2-1 LNG ship parameters and dimensions

(Noble 2009; Pratt et al. 2009)

LNG ship model parameters	Specification and values	Units
Model name and ship name	Q-max ship (MOZAH)	-
Vessel type	LNG Tanker	-
Summer deadweight (DWT)	130,100	t
Length overall (LOA)	345	m
Beam	53.8	m
Depth	27	m
Loaded draft	12	m
Ship speed	19.5	knots
LNG carrying capacity	266,000	m ³
Year of construction	2008	-

2.3 Design of LH₂ Cargo Tanks

The primary purpose of the ship is to carry hydrogen, a very light but voluminous cargo. Its properties are listed in Table 2-2. A preliminary analysis indicated that a ship with approximately the similar size as that of the Mozah (see Table 2-1) could carry about 20000 tonnes of hydrogen if it is stored in four cylindrical tanks with two hemispherical ends. Although using four tanks is a suitable choice, it is not the only solution. The IMO

Intact IGC Code for Hydrogen (IMO 2016) was used as a guideline. Table 2-3 shows the main characteristics of the tanks, which were determined considering preliminary mechanical sizing, thermal considerations, and liner application.

Table 2-2 Physical properties of hydrogen

(Bourne 2012; Colozza and Kohout 2002)

Property	Hydrogen	Unit
Density (gaseous)	0.089	kg/m ³ (@ 0 °C, 1 bar)
Density (liquid)	70.79	kg/m ³ (@ -253 °C, 1 bar)
Boiling point	-253	°C (@ 1 bar)
Energy per unit of mass (LHV)	120.1	MJ/kg
Energy density (ambient conditions, LHV)	0.01	MJ/L
Specific energy (liquefied, LHV)	8.4	MJ/L
Flame velocity	346	cm/s
Ignition range	4–77	% in air by volume
Autoignition temperature	585	°C
Ignition energy	0.02	MJ

Note: LHV = lower heating value

Table 2-3 Primary LH2 tank design parameters

LH ₂ tank input parameters	Parameter value	units
Mass of LH ₂ (M_{LH_2})	5,000	t
Pressure inside the tank (P_{LH_2})	0.5	MPa
Temperature inside the tank (T_{in})	20	k
LH ₂ density (ρ_{LH_2})	71	kg/m ³
Excess volume (V_i)	0.252	%
Tank cylinder section length (L)	111.6	m
Total internal length of hemisphere and cylinder sections (L_{total})	138	m
Total external length of hemisphere and cylinder sections (L_{et})	141.36	m
Yield strength of aluminium (4.4% Cu) (σ_y)	410	MPa
Design factor of safety (FOS)	54	-
Aluminium density (4.4% Cu) (ρ_t)	2,800	kg/m ³

2.3.1 Mechanical Sizing

The mechanical design of the tank wall is critical to addressing the liquefied hydrogen pressure load. It is assumed that the insulation and liner do not offer any construction strength. The tank volume is calculated, including the additional volume needed for boil-off, resulting in a bigger and heavier tank than would be required for other fuel types. The volume of an LH2 tank to store the required mass of hydrogen is calculated using the following equation (Colozza and Kohout 2002; Goldberg 2017):

$$V_t = \frac{M_{LH_2}}{\rho_{LH_2}}(1 + V_i). \quad 2-1$$

Mechanically, in order to achieve the total volume requirements of liquefied hydrogen, the tank design should consider the inner radius (r) in the case of a cylindrical tank with hemispherical end caps. The tank volume (V_t) is a function of the length of the cylinder section (L) and the inner radius of the tank (r), which can be determined by utilising the following equation:

$$V_t = \frac{4\pi r^3}{3} + \pi r^2 L. \quad 2-2$$

The authors considered that the liquefied hydrogen pressure is 0.5 MPa at the temperature of -252.76°C to carry the hydrogen in the liquid form (Benner et al. 2004; Bottini 2008; Petrucci and Harwood 2007). The wall thickness (t_w) for a cylindrical tank with hemispherical end caps can be determined as follows:

$$t_w = \frac{r P_{LH_2}}{2\sigma_y} FOS. \quad 2-3$$

The outer wall thickness relies upon the yield strength of the wall material and the design factor for safety (FOS), which is very significant to increase the tank safety, decrease the boil-off, and increase the tank weight to ensure the stability of the ship when carrying a large amount of liquefied hydrogen. Finally, the weight of the tank (M_t) depends on the tank material, which, in this study, is aluminium (4.4% Cu). The weight can be calculated as follows:

$$M_t = \rho_t \left[\frac{4\pi(r+t_w)^3}{3} + \pi(r+t_w)^2 L - V_t \right]. \quad 2-4$$

2.3.2 Thermal Sizing

In this study, the insulation is chosen such that the LH_2 need not be refrigerated during the journey. This significantly increases the size of the tank but obviates the need for expensive and complex refrigeration equipment on board; thus, the trade-off is considered acceptable. An iterative approach is implemented, and the insulation thickness of the polyurethane foam is initially assumed to be 1 m. This would limit boil-off to 0.1% of the total LH_2 quantity for each tank on board to keep the liquefied

hydrogen inside the tank at a constant pressure during the journey. The authors assumed no air in the polyurethane rigid closed-cell insulation foam due to the aluminium (4.4% Cu) wall thickness, which was calculated as 0.434 m to protect the polyurethane rigid closed-cell foam from the air; this thickness was distributed across two walls. The outer wall is made of aluminium (4.4% Cu) with 0.217 m thickness, and the inner wall has the same material and thickness as shown in Figure 2-1.

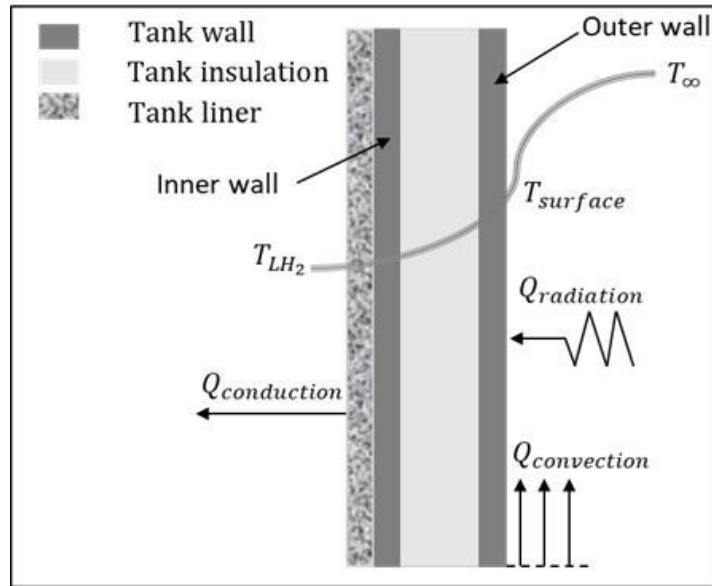


Figure 2-1 Heat transfer for liquefied hydrogen tank layers

The pressure in the tank containing the liquid hydrogen cargo will not increase owing to the boil-off of hydrogen because the boiled-off hydrogen will be extracted directly from the cargo tanks and supplied to the power plant of the ship as fuel. However, the design pressure of the tank is greater than the highest tank pressure during the voyage owing to the high insulation wall thickness of the tank; the design pressure of the tank is related to the value of the safety factor, which is high in this study. It is expected that a standby venting system will be needed on board for the occasions when the loaded ship is waiting in a harbour. Figure 2-1 shows the heat transfer processes and temperature variation through the insulation layers of the liquefied hydrogen tank. The figure shows the temperature transitions from the external ambient temperature T_{∞} to the insulation surface temperature $T_{surface}$, and finally, the internal tank temperature of liquefied hydrogen T_{LH_2} . The iterative process involves the calculation of the boil-off and the mass of insulation. The iteration starts with an estimation of the aforementioned

insulation thickness. The insulation surface temperature (T_{surface}) depends on the heat flow into the insulation layer via convection and radiation along with the heat flow into the tank by conduction through the insulation wall (Colozza and Kohout 2002); this value is assumed to be within the range of 258 K, i.e., the base temperature to 318 K, i.e., the most extreme temperature, to support the ship's voyage in various environments. Then, it is confirmed that equal amounts of heat flow into and out of the liquefied hydrogen inside the tank through the tank insulation. Finally, the authors determine whether the boil-off meets the required targets (Colozza and Kohout 2002; Goldberg et al. 2017), as follows:

$$Q_{in} = Q_{\text{convection}} + Q_{\text{radiation}}, \quad 2-5$$

$$Q_{out} = Q_{\text{conduction}}, \quad 2-6$$

where Q_{in} is the amount of heat flow to the tank insulation; this amount is a result of the incorporation of convection $Q_{\text{convection}}$ and radiation $Q_{\text{radiation}}$ heat flows. Q_{out} is the heat flowing out of the insulation layer to the liquefied hydrogen inside the tank, which represents the value of the conduction $Q_{\text{conduction}}$ heat flow. Each element of the heat transfer is calculated as follows:

$$Q_{\text{conduction}} = \frac{K(T_{\text{surface}} - T_{\text{LH}_2})}{L}, \quad 2-7$$

where K is the insulation thermal conductivity, which depends on the insulation material, and T_{LH_2} is the internal tank temperature.

$$Q_{\text{convection}} = h(T_{\infty} - T_{\text{surface}}), \quad 2-8$$

where h is the convection coefficient of the air surrounding the tank, and T_{∞} is the value of the temperature transition from the surroundings.

$$Q_{\text{radiation}} = \varepsilon \sigma (T_{\infty}^4 - T_{\text{surface}}^4), \quad 2-9$$

where σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$), and ε is the emissivity of the insulation surface. The following equation is used to calculate the convection coefficient:

$$h = \frac{N_{UD} K_g}{D}, \quad 2-10$$

Where N_{UD} is the Nusselt number, whose value depends on the geometry of the tank; K_g is the thermal conductivity of air, and D is the diameter of the tank. The next step is to calculate the Nusselt numbers for spherical and cylindrical shapes and add the obtained values to determine the correct Nusselt number for the LH_2 tank design:

$$N_{UD.cylinder} = \left(\frac{0.60 + 0.387 R_{ad}^{\frac{1}{4}}}{\left[1 + \left(\frac{0.559}{PR} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}} \right)^2 \text{ and } N_{UD.sphere} = \frac{2 + 0.589 R_{ad}^{\frac{1}{4}}}{\left[1 + \left(\frac{0.469}{PR} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}}, \quad 2-11$$

Where PR is the Prandtl number, and R_{ad} is the Rayleigh number. These can be calculated using the following equations:

$$PR = \frac{\alpha}{\nu}, \quad 2-12$$

$$R_{ad} = \frac{B_v(T_{\infty} - T_{surface})D^3}{\nu \alpha}, \quad 2-13$$

where B_v is the volumetric thermal expansion coefficient, and ν and α can be calculated using the following equations:

$$\alpha = -3.119 \times 10^{-6} + 3.541 \times 10^{-8} T_{\infty} + 1.679 \times 10^{-10} T_{\infty}^2, \quad 2-14$$

$$\nu = -2.079 \times 10^{-6} + 2.777 \times 10^{-8} T_{\infty} + 1.077 \times 10^{-10} T_{\infty}^2, \quad 2-15$$

$$B_v = \frac{1}{T_{\infty}}. \quad 2-16$$

The next step is to calculate the boil-off rate, $M_{boil\ off}$ ($kg\ s^{-1}$) of the liquid hydrogen using the following equation (where h_{fg} is the latent heat of vaporisation of liquid hydrogen):

$$M_{boil\ off} = \frac{Q_{conduction}}{h_{fg}}. \quad 2-17$$

The following equations are used to calculate the inner insulation radius (R_1), outer insulation radius (R_2), and the insulation thickness ($t_{insulation}$) required for the tank:

$$R_1 = r + t_w, \quad 2-18$$

$$R_2 = R_1 + t_{\text{insulation}}, \quad 2-19$$

where $t_{\text{insulation}}$ is assumed to be 1 m following a scale up from Goldberg et al. 2017.

Finally, the mass of insulation foam can be calculated using the following equation, where the density of the rigid open-cell polyurethane is 32.1 kg/ m³:

$$M_{\text{insulation}} = \rho_{\text{insulation}} \left[\frac{4\pi(R_2^3 - R_1^3)}{3} + \pi(R_2^2 - R_1^2)L \right]. \quad 2-20$$

The results of the thermal sizing calculations show that the insulation layer thickness and weight of the polyurethane foam are 1 m and 14.5 tonnes, respectively, and the boil-off rate is 0.1%. The calculation of boil-off is based on the range of the tank surface temperature, which is between 258 K to 318 K. This range is applicable to different weather conditions on most ship voyages; this changing in-tank surface temperature will produce a change in the boil-off rate. However, in the maximum surface temperature scenario, the boil-off rate will not breach the limit of 0.1%.

2.3.3 Tank Liner

The tank liner is important for preventing hydrogen gas from leaking through the walls. An impermeable layer is required to prevent LH₂ loss in case the material of the tank wall structure becomes somewhat permeable. In this study, the tank liner thickness is assumed to be 24 cm, and the required mass of the tank liner is calculated using the following equation, where the aluminium alloy liner (Al-Mg 5086) density (ρ_{liner}) is 2,660 kg/m³:

$$M_{\text{liner}} = \rho_{\text{liner}} \left[\frac{4\pi(r + t_{\text{liner}})^3}{3} + \pi(r + t_{\text{liner}})^2 L - V_t \right] \quad 2-21$$

Finally, in this stage, the total design weight of the LH₂ tank is determined to be the main element in the design and stability of the liquefied hydrogen ship, and it can be calculated using the following equation:

$$M_{\text{total LH}_2 \text{ tank}} = M_t + M_{\text{insulation}} + M_{\text{liner}}. \quad 2-22$$

Figure 2-2 represents a Cross-section of the LH₂ tank final design, and Table 2-4 shows the output results of the liquefied hydrogen tank design model.

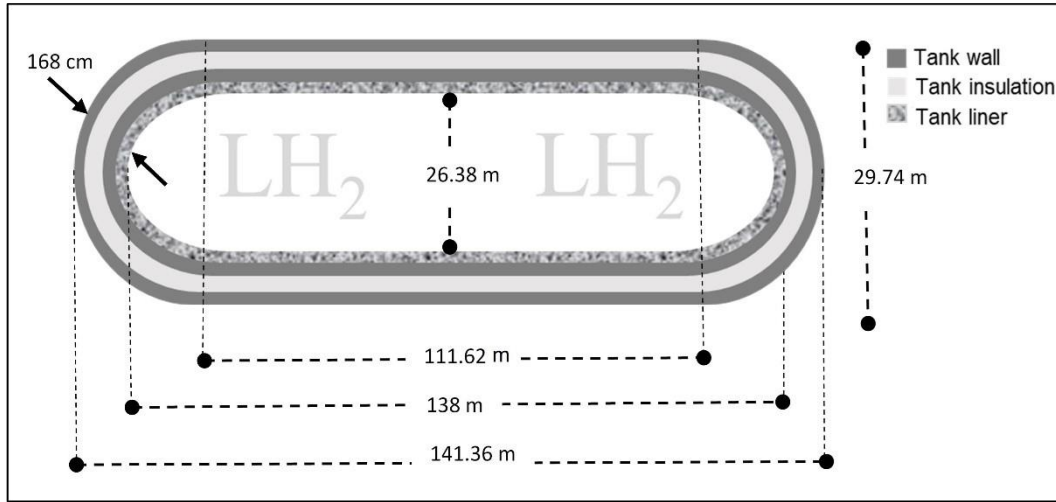


Figure 2-2 Cross-section of LH₂ tank design (not to scale). The 168-cm-thick wall includes 100 cm of rigid open-cell polyurethane foam insulation, 43.4 cm of aluminium, and 24.6 cm of aluminium alloy liner (Al-Mg 5086).

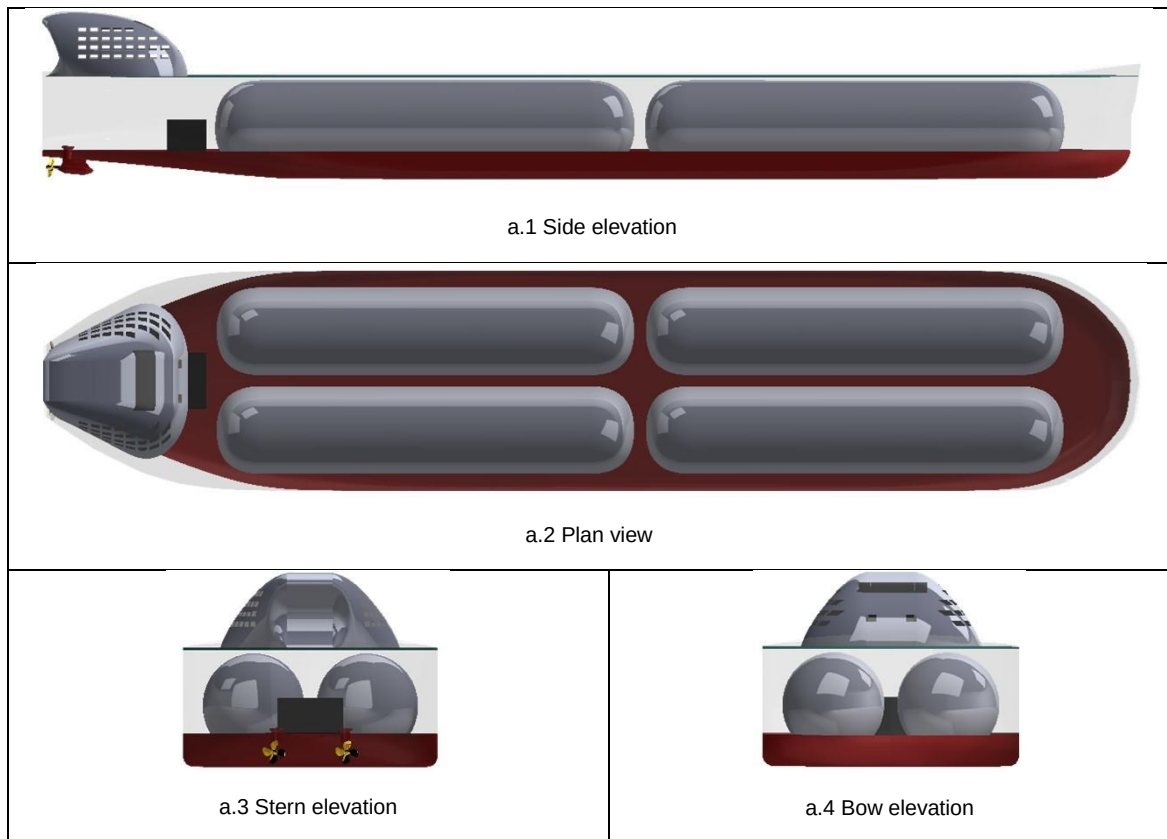
Table 2-4 Output results of the liquefied hydrogen tank design model

LH ₂ tank output parameters	Parameter value	units
Required volume of LH ₂ tank (V_t)	70,600	m ³
Tank inner radius (r)	13.19	m
Tank wall thickness (t_w)	0.434	m
Tank weight with wall only (M_t)	14,226	t
Boil-off rate	0.1	%
Inner insulation radius (R_1)	13.624	m
Outer insulation radius (R_2)	14.624	m
Mass of insulation polyurethane foam ($M_{insulation}$)	14.5	t
Mass of tank liner (M_{liner})	7,715	t
Total weight of the LH ₂ tank ($M_{total\ LH_2\ tank}$)	21,955	t

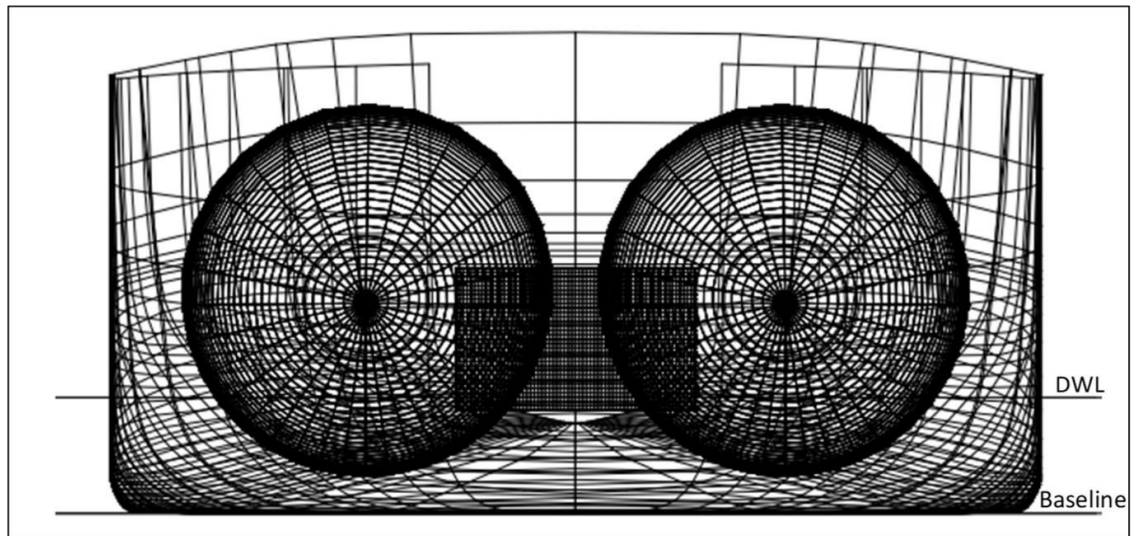
2.4 Hull Characteristics and Stability Evaluation

Once the tank dimensions were confirmed, the authors opted for a cylindrical bow and a twin-screw propulsion arrangement using an azimuthal podded drive system. The design of the cargo tanks was followed by the design of a ship to fit the tanks. Figure 2-3 shows the final characteristics of JAMILA. These were the results of the detailed evaluations of the design dimensions of the ship hull to commensurate with the unusually light ship deadweight. The curves in Figure 2-3b and Figure 2-3c were

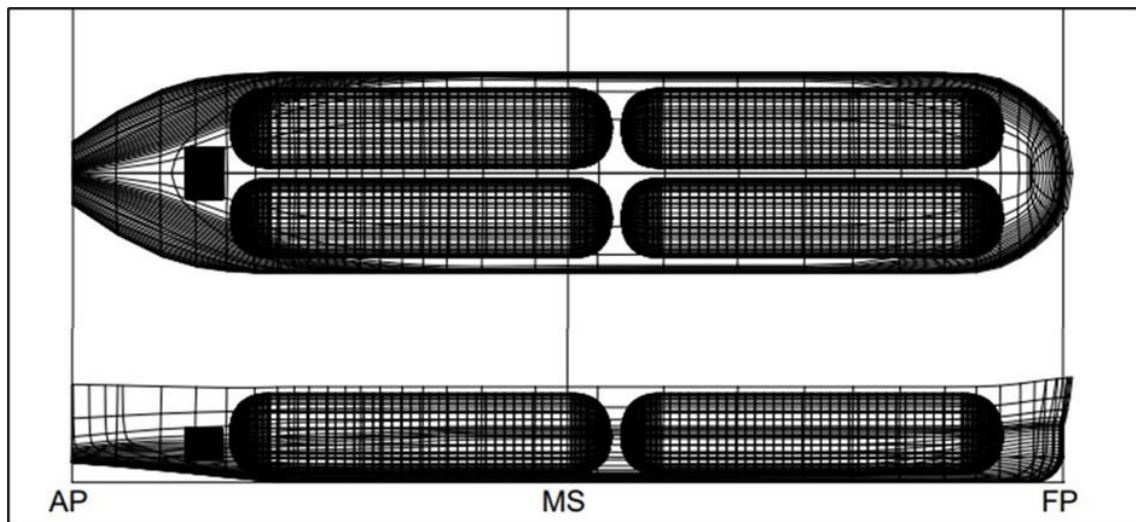
produced using the Maxsurf Software (Bentley Systems 2016), taking into consideration certain key parameters of the ship such as the block coefficient, the type of bow, the type of stern, and a few other details as the main inputs for the loaded and unloaded conditions.



(a)



(b)



(c)

Figure 2-3 (a) JAMILA LH₂ tanker ship (3D model); (b) perspective and water line; (c) profile ship aft and forward perpendicular

Table 2-5 presents the design values of the weights, dimensions, volumes, and power of the liquefied hydrogen tanker, which was powered by a 50 MW combined-cycle gas turbine. The increased weight of the liquefied hydrogen ship hull and tanks due to the high hydrogen volume will balance the density between LNG and LH₂, which indicates similar power requirements for the liquefied hydrogen and liquefied natural gas tankers. The specifications of the LH₂ tanker are rather unusual. The design deadweight (DWT)

is 20,000 tonnes, which is very low for a ship of this size. This is due to the exceedingly low density of the cargo.

Table 2-5 Main parameters and dimensions of the ship

LH₂ tanker parameters	Values	Units
Class	JAMILA	-
Vessel type	LH ₂ Tanker	-
Total displacement (Δ_{total})	232,000	tonnes
Lightweight (LWT)	210,000	tonnes
DWT	22,000	tonnes
LOA	370	m
Length between perpendicular (<i>LBP</i>)	367.5	m
Length on the water line (<i>LW</i>)	367.9	m
Extreme breadth (<i>B</i>)	75	m
Depth (<i>D</i>)	35	m
Draft (<i>T</i>) (full load condition)	10.012	m
Draft (<i>T</i>) (unload condition)	9.263	m
Block coefficient (C_B) (full-load condition)	0.819	-
Block coefficient (C_B) (unloaded condition)	0.813	-
Ship speed	18	knots
LH ₂ cargo tank weight (Aluminium)	87,819 (2,955 x 4)	tonnes
LH ₂ cargo tank capacity	282,400 (70,600 x 4)	m ³
LH ₂ cargo weight	20,000 (5,000 x 4)	tonnes
LH ₂ engine fuel tank weight (Aluminium)	4,370	tonnes
LH ₂ engine fuel tank capacity	14,099	m ³
LH ₂ engine fuel weight (20-day return journey + 2-day ship idle period + 100 tonne reserve)	1,278	tonnes
Rate of boil-off from cargo	0.1 (20 tonne/day)	% per day
Fuel-saving percentage due to boil-off	29%	%
Voyage range	450 to 4,400	Nautical mile
Minimum propulsion power required for the fully loaded condition	27.3	MW
Combined cycle gas & steam installed	50	MW

2.4.1 Ship Stability Estimation

To calculate the ship stability (Figure 2-4), the metacentric height (*GM*) was determined (Barrass and Derrett 2011; Lewis 1988) as follows:

$$GM = KM - KG = KB + BM - KG. \quad 2-23$$

The value of *KG* can be calculated using the following equation:

$$KG = \frac{\Sigma \text{moment about the keel}}{\Delta_{total}}. \quad 2-24$$

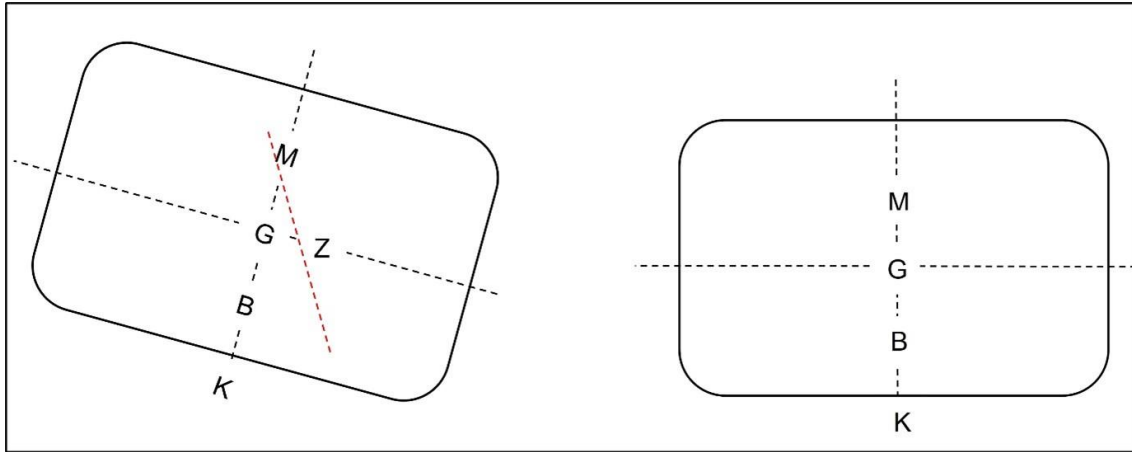


Figure 2-4 Righting arm (GZ) with the vessel heel due to external force

To calculate the transverse moment of inertia (I_T) of the waterplane about the centreline, the weight of the ship's components and the distance of those components from the keel need to be estimated based on the data in Table 2-6 and Table 2-7. The weights of the ship components were determined using an estimation-based iterative process through comparison with similar types of ships (Moore 2010). There is a small uncertainty in this hydrogen tanker data. This uncertainty is small in relation to other component weights. Other uncertainties also arise from the integration of the tanks into the hull; hence, the masses of the tank structure, auxiliaries, and equipments are relatively large. Moreover, some of these components were placed on the ship to optimise the vertical centres of gravity under the loaded and unloaded conditions. The flexibility of the turboelectric propulsion system is helpful in this context.

Table 2-6 Centres of gravity under the unloaded condition

Component	Mass (t)	VCG (m)	I_T (m.t)
LH ₂ cargo tanks	87,819	16.350	1,436,000
LH ₂ fuel tank	4,370	30	131,100
Engine and stern gear	8,000	10	80,000
Hull structure	51,000	17.5	898,000
Deck gear, anchor, cables, pipes, crew	5,000	37.5	187,500
Accommodation	2,200	42.5	93,500
LH ₂ tanks, accessories and equipments	52,000	10.25	533,000
Fuel	1,278	30	38,500
Low-pressure hydrogen	1,000	16.350	16,350
$\sum$ moment about the keel			3,414,000
Unloaded $KG = 16.028$ m			

Table 2-7 Centres of gravity under the loaded condition

Component	Mass (t)	VCG (m)	I_r (m.t)
LH ₂ cargo tanks	87,819	16.350	1,436,000
LH ₂ fuel tank	4,370	30	131,100
Engine and stern gear	8,000	10	80,000
Hull structure	51,000	17.5	898,000
Deck gear, anchor, cables, pipes, crew	5,000	37.5	187,500
Accommodation and crew	2,200	42.5	93,500
LH ₂ tank accessories and equipment	52,000	10.25	533,000
Fuel	1,278	30	38,500
Hydrogen cargo	20,000	16.350	327,000
$\sum$ <i>moment about the keel</i>			3,725,000
<i>Loaded KG = 16.054 m</i>			

2.4.2 Ship Stability Verification

The metacentric height has a positive value, which indicates that JAMILA exhibits suitable stability characteristics. The manually calculated values were verified with the aid of software (Bentley Systems 2016). In general, the following results provide a partial answer to the question, ‘what would a hydrogen ship look like? Table 2-8 shows the validation of the manually calculated stability values, specifically, the main ship characteristics and coefficients under the loaded and unloaded conditions. These results are used to confirm the primary output values of the ship stability calculations. A small difference exists between the results under the two conditions owing to the extremely low density of the cargo.

Table 2-8 Hydrostatic results under different drafts

Draft Amidships m	9.263 (Unloaded)	10.012 (Loaded)	Unit
Displacement	213,000	232,000	tonnes
Draft at FP	9.263	10.012	m
Draft at AP	9.263	10.012	m
WL Length	367.87	367.98	m
Beam maximum extents on WL	75.000	75.000	m
Wetted Area	28,916	29,551	m ²
Waterplane Area	24,677	24,837	m ²
Prismatic coefficient (C _p)	0.818	0.824	-
Block coefficient (C _b)	0.813	0.819	-
Midship section area coefficient (C _m)	0.994	0.995	-
Waterplane area coefficient (C _{wp})	0.894	0.900	-
LCB from zero pt. (+ve fwd)	202	201	m
LCF from zero pt. (+ve fwd)	193	192	m
KB	4.840	5.233	m
KG	16.028	16.054	m

BM_t	50.358	46.606	m
BM_L	1,113	1,040.9	m
GM_t	39.171	35.785	m
GM_L	1,103	1,030	m
KM_t	55.199	51.839	m
KM_L	1,118.3	1,046.2	m
Immersion (TP_c)	252.94	254.58	tonne/cm
MT_c	6,381.7	6,496	tonne.m
RM at 1 deg	145,612	144,894	tonne.m

Figures 2-5, 2-6 and 2-7 show the hydrostatic curves, geometric coefficients, and stability details of the ship, respectively. These figures present the outputs of the Maxsurf evaluation for the inputs mentioned earlier. Figures 2-5, 2-6 and 2-7 clearly indicate the hydrostatic values in the loaded and unloaded conditions of the ship.

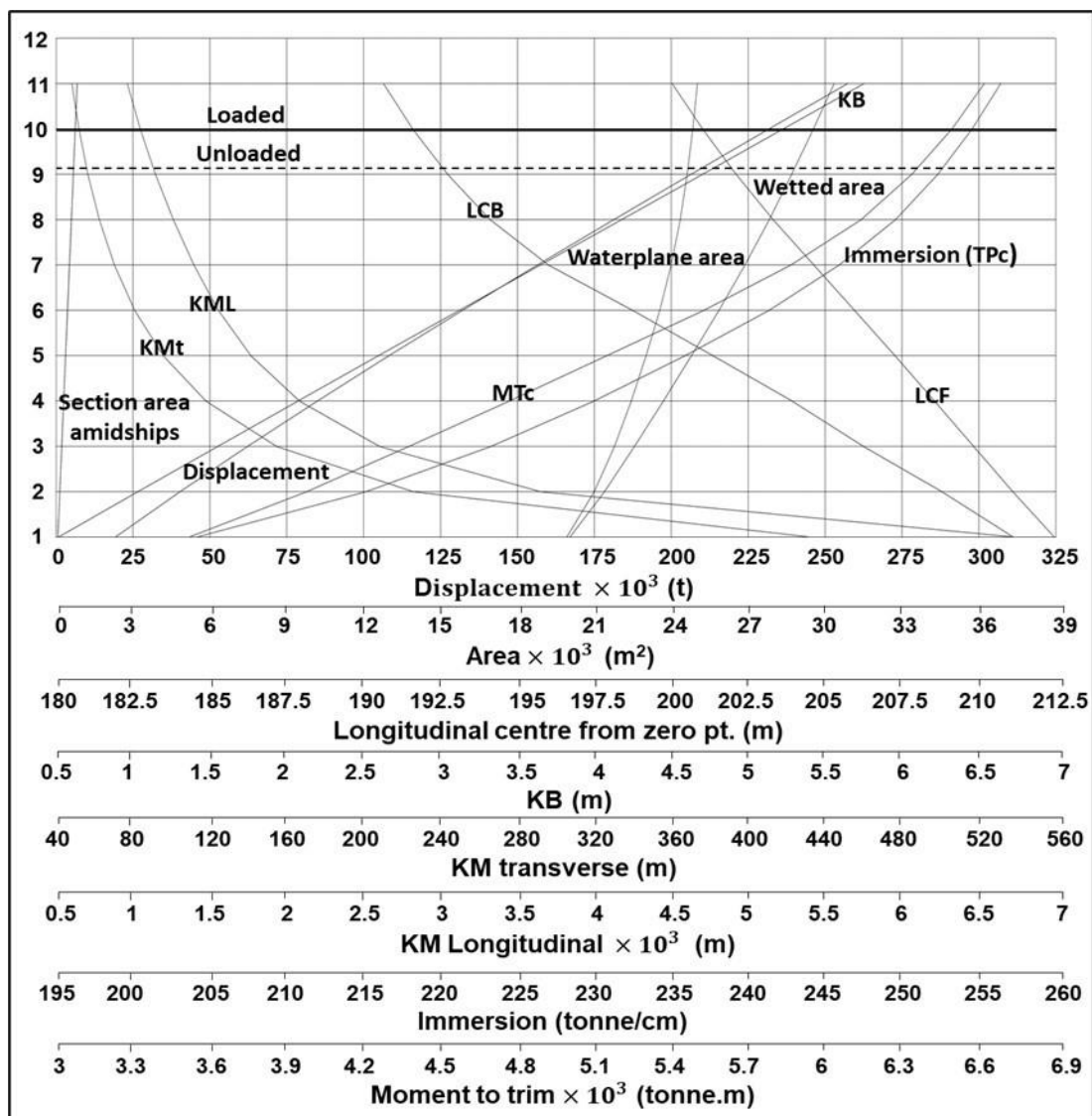


Figure 2-5 Ship hydrostatic diagram: characteristics vs draft (m)

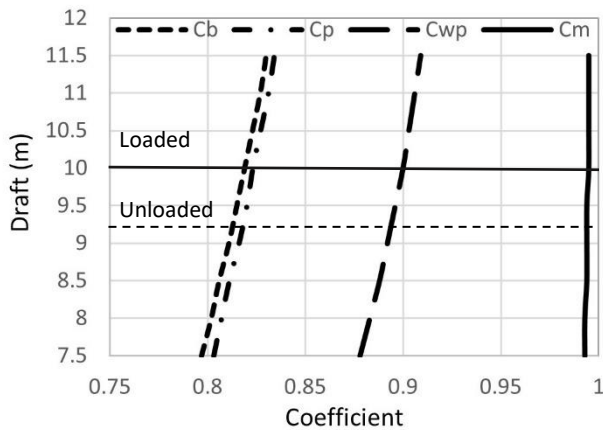


Figure 2-6 Ship coefficients for different drafts

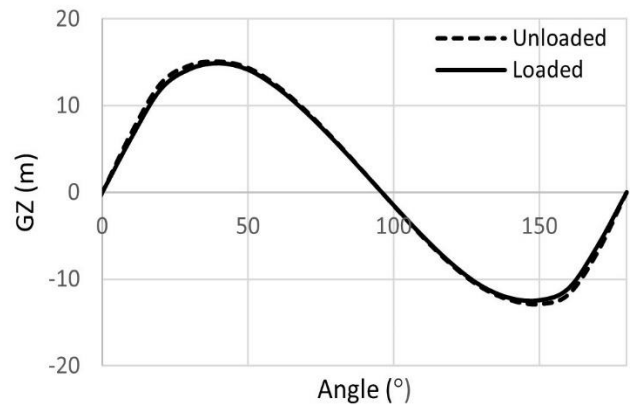


Figure 2-7 Righting arm curve (GZ)

Based on Table 2-9, the intact stability of JAMILA is subject to the 2008 IMO Intact Stability Code (ISC) (IMO, 2008):

1. Metacentric height (GM) ≥ 0.15 m.
2. Area under the static stability curve (GZ) up to $30^\circ \geq 0.055$ mrad.
3. Area under the static stability curve (GZ) up to down-flooding angle (ϕ_f ; 40°) ≥ 0.090 mrad.
4. Area under the static stability curve (GZ) from 30° to ϕ_f (40°) ≥ 0.030 mrad.
5. The righting lever $GZ \geq 0.2$ m at the angle of heel is equal to or greater than 30° .

The maximum value of the righting lever (GZ) occurs at $\phi > 25^\circ$.

**Table 2-9 IMO ship criteria under the unloaded and loaded conditions
(IMO, 2019)**

Criterion	Values & units	Status	Actual (unloaded)	Margin % (unloaded)	Actual (Loaded)	Margin % (Loaded)
3.1.2.1: Area 0 to 30	3.1513 m.deg	Pass	272.2	Very Large	256.93	Very Large
3.1.2.1: Area 0 to 40	5.1566 m.deg	Pass	421.4	Very Large	403.5	Very Large
3.1.2.1: Area 30 to 40	1.7189 m.deg	Pass	149.2	Very Large	146.6	Very Large
3.1.2.2: Max GZ at 30 or greater	0.200 m	Pass	15.055	Very Large	14.9	Very Large
3.1.2.3: Angle of maximum GZ	25.0°	Pass	39.1	+56.36	40.0	+60.00
3.1.2.4: Initial GMt	0.150 m	Pass	39.205	Very Large	35.793	Very Large
3.1.2.5: Passenger crowding: angle of equilibrium	10.0°	Pass	N/A	+100.00	N/A	+100.00
3.1.2.6: Turn: angle of equilibrium	10.0°	Pass	N/A	+100.00	N/A	+100.00
Angle of steady heel shall not be greater than ($\leq$)	16.0°	Pass	0.1	+99.64	0.1	+99.64

Angle of steady heel / Deck edge immersion angle shall not be greater than ($\leq$)	80.00%	Pass	0.57	+99.29	1.06	+98.67
Area1/Area2 shall not be less than ($\geq$)	100.00%	Pass	281.34	+181.34	290.64	+190.64

2.5 Conclusion

The LH₂ tanker ship assessed in this research is 370 m long, 75 m wide, and draws 10.012 m under the fully loaded condition. The fully loaded displacement tonnage is 230,000 tonnes to transport 20,000 tonnes of hydrogen. Its power system is a combined-cycle gas turbine of roughly 50 MW. The size and displacement of the ship depend largely on its required capacity to transport liquefied hydrogen (a very light but voluminous substance) at 0.5 MPa.

The specifications of the LH₂ tanker are highly unusual. The DWT is slightly larger than 20,000 tonnes, which is very low for a tanker of these dimensions. This is the result of the very low density of the cargo and should be expected for any LH₂ tanker. Another outcome of the low density of the cargo is a relatively small difference in the draft (slightly less than 1 m) between the loaded and unloaded conditions of the ship. The proposed design includes a high freeboard. This is not unusual in shipping applications, for which LNG carriers, cruise ships, and aircraft carriers are designed with high freeboards or very high and long superstructures.

The calculations for the ship evaluation were performed conventionally and verified using special software. Although the preliminary design proposed herein is not the only solution, it is a viable one and offers a philosophical view of what an LH₂ tanker could look like. There are several aspects that require further attention, but they are not expected to have a major impact on the overall ship design and characteristics.

The ship resistance, power requirements, and power plant performance were evaluated, and these are described in the next stage of this investigation, which will be published separately. The power required was estimated to be approximately 50 MW under the fully loaded condition to enable a service speed of 18 knots. A hydrogen-fuelled combined-cycle gas turbine is proposed for this purpose.

There is a growing consensus that the need to decarbonise human activities will elevate the importance of hydrogen in our everyday lives. The high cost of its implementation is gradually becoming more acceptable in view of the environmental and economic benefits that it offers. The design proposed here is a viable one. Investments in ships that are similar to the vessel evaluated herein are an important prerequisite for the decarbonisation process.

ACKNOWLEDGEMENT

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DECLARATION OF INTEREST

No potential competing interest is reported by the authors

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3 PAPER 2 - PROPULSION OF A HYDROGEN-FUELLED LH₂ TANKER SHIP

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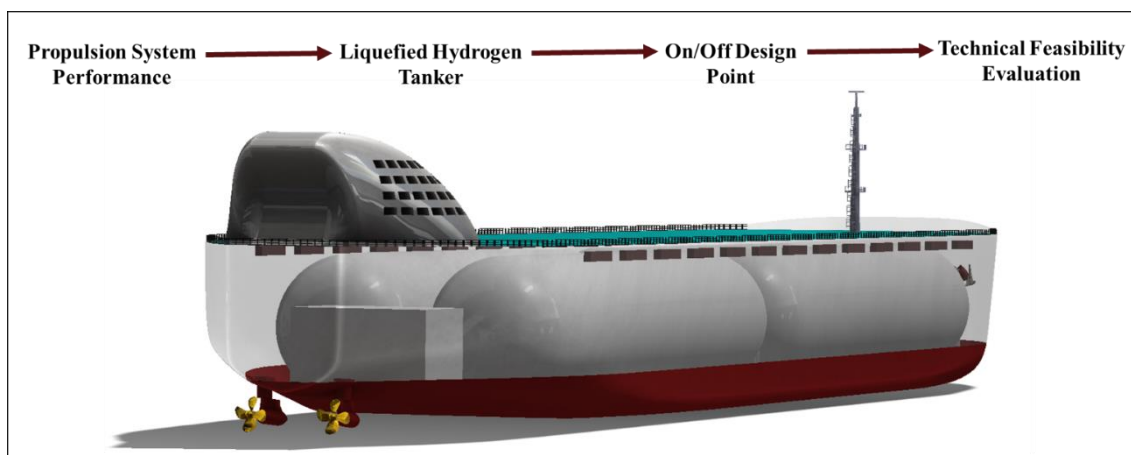
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Abstract

This study aims to present a philosophical and quantitative perspective of a propulsion system for a large-scale hydrogen-fuelled liquid-hydrogen (LH₂) tanker ship. Established methods are used to evaluate the design and performance of an LH₂-carrier propulsion system for JAMILA, a ship designed with four cylindrical LH₂ tanks bearing a total capacity of ~280,000 m³ along with cargo and using the boil-off as propulsion and power fuel. Additionally, the ship propulsion system is evaluated based on the ship resistance requirements, and a hydrogen-fuelled combined-cycle gas turbine is modelled to achieve the dual objectives of high efficiency and zero-carbon footprint. The required inputs primarily involve the off-design and degraded performance of the gas-turbine topping cycle, and the proposed power plant operates with a total output power of 50 M.W. The results reveal that the output power allows ship operation at a great speed even with a degraded engine and adverse ambient conditions.

Graphical abstract:



KEYWORDS: Liquefied hydrogen; LH₂ tanker; Ship design; Liquid hydrogen tank; Propulsion system

NOMENCLATURE

Symbol	Meaning	Symbol	Meaning
A_{BT}	Transverse bulb area	Q	Propeller torque
A_E/A_O	Propeller blade area ratio	$Q_{3-4} = Q_{e-d}$	Heat transfer in gas side from heat recovery steam generator (HRSG)
A_T	Immersed part of the transverse sectional area of transom at A.P. at zero speed	Q_{1-3}	Heat exchanged above the pinch
B	Ship breadth extreme	R_A	Model-ship correlation resistance
C	Coefficient that accounts for the specific shape of the afterbody	R_{APP}	Appendage resistance
C_A	Correlation allowance coefficient	R_B	Additional pressure resistance of bulbous bow
C_B	Block coefficient	R_F	Frictional resistance
C_F	Frictional resistance coefficient	$R_F(1 + k_1)$	Viscous hull resistance
C_m	Midship section area coefficient	R_n	Reynolds number
C_p	Prismatic coefficient	R_T	Total resistance
c_p	Specific heat constant pressure	R_{TR}	Additional pressure resistance of the immersed transom stern
C_{stern}	After body coefficient	R_W	Wave resistance
C_{Wp}	Waterplane area coefficient	S_{APP}	Wetted surface area of appendage
D	Ship depth	S_{BH}	Wetted surface area of bare hull
D.P	Design point	S_i	Steam turbine input entropy
D_{pr}	propeller diameter and	S_o	Steam turbine outlet entropy
DWT	Ship deadweight	S_{og}	Gas outlet steam entropy
F_n	Froude number	S_{of}	Fluid outlet steam entropy
g	Gravitational acceleration	T	Ship draft
GTCC/COGAS	Gas turbine combined cycle	t	Thrust deduction factor
h	Value of shaft immersion depth	t/c	Thickness to chord length ratio
h_a	Superheat steam enthalpy	T_a	Superheat temperature
h_B	Vertical position of the centroid of A_{BT} above the baseline	T_c, T_b	Saturation temperatures
h_d	Economiser outlet enthalpy	T_d	Economiser outlet temperature
h_i	Steam turbine input enthalpy	T_e	Feed water temperature
h_{iso}	Isentropic outlet steam enthalpy	T_F	Forward draught of the ship
h_{oact}	Actual outlet steam enthalpy	T_H	Propeller thrust required
h_{of}	Fluid outlet steam enthalpy	T_{Hg}	Propeller thrust generated
h_{ofg}	Fluid and gas outlet steam enthalpy	T_1	Gas turbine exhaust temperature
i_E	Angle of the waterline at the bow	T_3	Pinch point temperature on gas side
J	Advance ratio	T_4	Stack temperature
K_Q	Propeller torque coefficients	V	Ship speed
K_T	Propeller thrust coefficients	ν	seawater kinematic viscosity
LBP	Length between perpendicular	V_A	speed of advance
lcb	Longitudinal centre of buoyancy	w	Effective wake fraction
LH ₂	Liquefied hydrogen	W_{CC}	Total combined cycle output power
LNG	Liquefied natural gas	W_{GT}	Gas turbine output power
LOA	Length overall	W_{pump}	Pump work
L.R.	Length of the run	W_{ST}	Steam turbine output power
L.W.	Length of water line	X	Outlet steam quality
LWT	Ship lightweight	Z	Propeller blade number
m_g	Gas mass flowrate	ΔT_a	Approach point temperature difference
m_s	Steam mass flowrate	ΔT_p	Pinch point temperature difference
NOx	Nitrogen oxide	Δ_{total}	Ship total displacement
n	Revolutions of propeller per second	∇	Displacement volume of the ship
OD. 1	Off design point	η_{CC}	Total combined cycle output efficiency
P/D_{pr}	Propeller pitch to diameter ratio	η_H	Hull efficiency
P_{atm}	Atmospheric pressure	η_R	Relative rotative efficiency
P_{BH}	Brake horsepower	η_{ST}	Steam turbine isentropic efficiency
P_{cond}	Condenser pressure	η_T	Transmission efficiency
P_{DH}	Propulsive horsepower	η_o	Propeller efficiency in open water
P_{EH}	Effective horsepower	λ	Wavelength of the dynamic load case
P_S	Steam pressure	ρ	The density of the sea water
P_{TH}	Ship required thrust horsepower	$1 + k_1$	Form factor
P_v	Vapor pressure of water	$1 + k_2$	Appendage resistance factor

3.1 Introduction

The International Maritime Organization (IMO)—the U.N. agency responsible for the safety of lives at sea, efficient shipping, and the prevention of pollution produced from international shipping—has drafted strict environmental regulations to reduce the impact of maritime shipping emissions on the global environment. In April 2018, the IMO adopted an initial strategy to reduce greenhouse gas (GHG) emissions from international maritime shipping by at least 50% by 2050 as compared to 2008 levels. This strategy additionally targets reducing CO₂ emissions from shipping by at least 40% and 70% by 2030 and 2050, respectively, as compared to 2008 levels [1]. This will reduce CO₂ emissions by maritime shipping, thereby decreasing its impact on the environment. Therefore, certain countries have already begun applying these new IMO regulations. Based on these new regulations, the United Kingdom published the U.K. Clean Maritime Plan in July 2019 to serve as an environmental road map and achieve the government's Maritime 2050 vision that intends to transition shipping in the U.K. waters to a zero-emissions future, wherein all new vessels in U.K. waters will be designed with zero-emissions propulsion capabilities by 2025 [2]. Accordingly, the development of alternative fuels and technologies is imminent to reduce maritime shipping emissions and address new international- and national-level requirements. In this context, liquefied hydrogen (LH₂) is gaining popularity as a considerable option for achieving the zero-carbon target of marine applications to ensure decarbonisation of the maritime sector in the future [3].

Hydrogen fuel can be potentially used for decarbonising thermal engines, provided the production of hydrogen is a carbon-free process, and the engines deliver very low amounts of NO_x. In addition, hydrogen removes additional harmful emissions such as unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot, and smoke. Hydrogen is a technology solution to provide sustainability in the maritime environment. However, unlike fossil fuels, hydrogen gas cannot be directly extracted from the earth but must be manufactured from various sources. In general, hydrogen can be produced from several sources, including water, biomass, and fossil fuels, using electrolysis, steam–methane reforming, and gasification [4,5]. However, technologies

that can produce hydrogen in cleaner ways are emerging. For instance, an electrolysis process that is a zero-CO₂ emissions technology has been developed to produce hydrogen by splitting water into hydrogen and oxygen directly without natural gas or CO₂ emissions by using solar energy [6]. Currently, global efforts are intending to produce a low-emission propulsion system as well as include carrying clean energy through hydrogen using large tanker ships [3]. In the future, hydrogen will be transported using a large-scale LH₂ carrier ship. However, saving weight and cargo space is a concerning issue in the maritime sector, especially for LH₂ tankers, because the density of hydrogen is extremely less as a voluminous substance. Thus, a combined-cycle gas turbine is a potential alternative for achieving compact engine size benefits with acceptable thermal efficiency targets [7].

Prior related research focuses on designing and evaluating a combined-cycle gas turbine as a marine propulsion system. In 2000, the 'Millennium' cruise ship was launched, which operates on a combined cycle including two 25-MW "LM2500+" gas turbines fuelled by marine gas oil (MGO) and a 9-MW steam turbine as a bottoming cycle [8,9]. In addition, Benvenuto et al. [10] developed mathematical models to optimise and compare the performance of several possible steam cycle configurations to employ a COGAS power plant for marine propulsion. The overall energy conversion efficiency of the installation, plant dimensions, weights, and economic considerations were all accounted as critical parameters in selecting a propulsion system.

However, Benvenuto et al. study provides vital fundamental information for evaluating the performance of marine COGAS propulsion systems without using liquefied hydrogen fuel [10,11]. The following research and projects aim at hydrogen as a ship propulsion system fuel to achieve emission reduction sustainability to protect the global from climate change expansion. Evrin and Dincer [36] integrated a hydrogen-fuelled fuel cell with a steam-producing cycle to supply ships electricity and freshwater using two heat recovery systems to provide ship thrust and drive the ship refrigeration cycle and assessed that the proposed model system vastly reduces greenhouse-gas emission. Feng Li et al. [37] Applied a numerical calculation using Fluent software to simulate the leakage and diffusion of hydrogen in a fuel cell ship and analyse the concentration distributions of hydrogen in the ship cabins under various ventilation circumstances to

offer a guide for the design of a fuel cell ship utilising high-pressure gaseous hydrogen. Mao X et al. [38] targeted a passenger ship powered by a hydrogen fuel cell and applied a numerical simulation on the leakage and explosion of hydrogen in different compartments on a ship using fluid computation software. McKinlay et al. [39] analysed the applicability of hydrogen fuel cells to be a suitable method of decarbonising the auxiliary services of current long-distance ships using LNG tanker data. This research has indicated that retrofitting a hydrogen fuel cell system to a current large-scale ship might theoretically make a meaningful reduction of emissions by meeting auxiliary load. In another study, McKinlay et al. [40] evaluated various viable options to achieve ships zero-emission propulsion target by 2025, with three promising alternative fuels hydrogens, ammonia and methanol. This is essentially owing to their possibility to generate emission-free electricity by using fuel cells. To the best of the authors' knowledge, the design and performance evaluation of hydrogen-fuelled combined-cycle gas turbines for marine applications has not been considered yet. Thus, the preliminary design of the hydrogen carrier ship [3] is required to be completed based on the prime-mover system of the LH₂ tanker ship, including the performance evaluation of a hydrogen-fuelled combined-cycle gas turbine as a maritime propulsion system.

This study aims to design and evaluate the performance of a hydrogen-tanker ship-propulsion system in design and off-design conditions. Using state-of-the-art design and analysis methods, the authors delivered on the prospect of such a ship propulsion system. However, the economic and cost analysis for the LH₂ propulsion system was beyond the scope of the current study. The feasibility aspect of the propulsion system was analysed using the Techno-economic Environmental Risk Analysis (TERA) method [12,13] and will be the focus of another manuscript in the future.

3.2 Design and Performance Differences with a Conventional Combined-Cycle Gas Turbine

This research proposes an extraordinary, philosophical approach to achieving zero-emission maritime transportation through the design and performance assessment of an untraditional combined cycle gas turbine as an LH₂ tanker prime mover. Thus, the approach suggested in this research is a derivative design, not a retrofit. Technically, the

design and performance of the combined cycle gas turbine were evaluated using TURBOMATCH (inhouse Cranfield gas turbine performance simulation code) [18] by applying conventional and hydrogen fuels. The TURBOMATCH analytical method utilises the performance principles of a gas turbine [41] and is a reiterative method based on gas turbine components characteristics. As estimated, there are no main variations caused by utilising hydrogen fuel in the engine performance compared with conventional fuel, as shown in Table 3-1.

Table 3-1 Gas turbine engine characteristics by applying conventional and hydrogen fuel.

Gas turbine characteristics	Conventional	Hydrogen	Units
Fuel flow	1.852	0.7485	kg/s
Mass flow	84.2	84.2	kg/s
Turbine entry temperature	1550	1550	K
Output power	34.7	36.2	MW
Exhaust mass flow	85.9	84.9	kg/s
Exhaust gas temperature	845.06	840.3	K
Compressor pressure ratio	23.1	23.1	-
COGAS			
Output power	48	50	MW
Thermal efficiency	54.5	55	%

3.2.1 Engine Performance Assessment

In order to characterise the difference of design method for hydrogen-fuelled combined-cycle gas turbine and conventional combined-cycle gas turbine, the authors selected the design point (D.P) of the COGAS fuelled by hydrogen as a ship prime mover based on engine simulation and the results of performance analysis in terms of gas turbine efficiency, specific power, and COGAS efficiency through the compressor pressure ratio variation at constant turbine entry temperature value (1550 K) in case of using hydrogen fuel and conventional fuel which is shown in Figure 3-1. The results indicated that the COGAS fuelled by hydrogen could achieve 55% as the highest efficiency with the compressor pressure ratio of 23.1 for the gas turbine design point. Moreover, Figure 3-1 shows that using hydrogen fuel achieved 4.5% higher specific work than conventional fuel due to combustion products containing no CO₂ and a larger quantity of H₂O, which has a higher specific heat at constant pressure value [42].

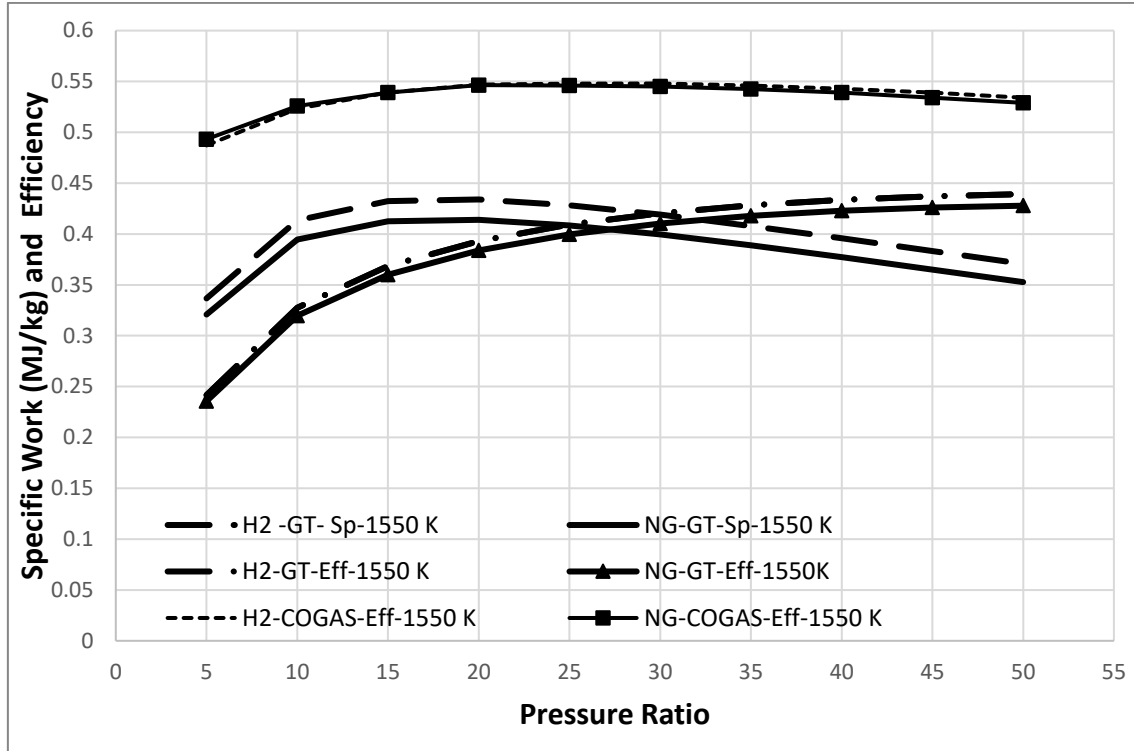


Figure 3-1 The specific work for gas turbine and efficiencies for the gas turbine and COGAS for various pressure ratios using conventional and hydrogen fuel in design point.

3.2.2 Hydrogen Gas Turbine Design

The gas turbine engine design fuelled by hydrogen was inspired by an LM2500+ industrial gas turbine engine fuelled by natural gas [28] as conventional fuel to achieve the ships power requirement. The design difference arises during the slightly different properties in the hot section of the gas turbine fuelled by hydrogen due to the same reason related to the combustion products containing no CO₂. Table 3-2 shows the changes in the gas turbine hot section areas with the velocity variation for each stage. The gas turbine fuelled by hydrogen simulation results shows that the combustor outlet and turbine inlet section's area increased around 3.1% compared with conventional fuel in the combustor. On the other hand, in the case of turbine outlet and power turbine inlet using hydrogen fuel, the section's area decreased around 0.002 m² compared with conventional fuel. In the case of a power turbine outlet using hydrogen fuel, the section's area increased around 1.6% compared with conventional fuel. Those changes are due to variability in each section's total inlet and outlet temperatures.

Table 3-2 Gas turbine hot section area changes in different velocities using conventional and hydrogen fuel.

Station	Velocity (m/s)	Conventional (m²)	Hydrogen (m²)
Combustor outlet	304	0.062	0.064
Turbine inlet	304	0.062	0.064
Turbine outlet	265	0.216	0.214
Power turbine inlet	265	0.216	0.214
Power turbine outlet	224	0.925	0.940

3.3 Overall Design Philosophy Description

Based on the preliminary design of the LH₂ tanker ship hull and the stability analysis conducted in a previous study [3], a suitable propulsion system design is required for this unique ship. The authors of this paper determined that the initial design concept of the LH₂-tanker ship-propulsion system depends on several factors based on the ship propulsion power requirements, such as ship dimensions, weights, resistance, speed, and hull design coefficients, considering the decarbonisation target and high thermal efficiency achievement. The primary stage of the ship propulsion system design includes the ship-module calculation of the brake power required from the propulsion system, prediction of ship hull resistance, and estimation of propulsion factors using a statistical method [14,15]. In particular, the total hull resistance was preliminarily calculated as a function of viscous hull resistance, appendage resistance, wave resistance, and model-ship correlation resistance, including the additional pressure resistance of the bulbous bow near the water surface, which was assumed as zero owing to the ship hull form design. Moreover, the additional pressure resistance of the immersed transom stern was assumed as zero owing to the ship design. The calculation of propulsion factors involved the prediction of the effective wake fraction, thrust deduction factor, and the relative rotational efficiency of the propulsion system established on the LH₂ carrier ship. In addition, the resistance estimation and the power required during loading and unloading conditions at various speeds were validated using the MAXSURF software.

Furthermore, the collaboration between the hull and propeller was represented via the power required by the combined-cycle gas turbine—known as the brake power from the effective power for the ship hull, which is a product of the total resistance and the LH₂ carrier ship speed. The authors used the Wageningen B-series propellers method to

estimate the twin-screw attached to the pods of the open-water propeller design and specify its characteristics [16]. However, the lightweight of hydrogen requires a distinct ship design, especially a small hull draft in the unloading condition, which eventually causes operation challenges in shallow water as compared to alternative tanker ships. Based on this distinct condition, the authors of this paper selected a turboelectric system including two azimuthal podded propellers with a maximum power output of 15.5 MW each as a component of the LH₂ carrier ship propulsion system. This selection supported the reliability and controllability of the LH₂ carrier ship in shallow waters. After the power requirements were determined, the power plant was required to be modelled for generating the power required for the vessel. Thus, the authors selected a hydrogen-fuelled combined-cycle gas turbine as the prime mover to generate power for the LH₂ propulsion system owing to its more compact size and dimensions, which is a vital consideration for the large volume of LH₂ cargo, lightweight, high thermal efficiency, and low emissions in comparison to two-stroke diesel engines [17]. The combined-cycle gas turbine, including a simple-cycle gas turbine and a single-pressure heat-recovery steam generator, was simulated with the capabilities of design and off-design point calculations based on the TURBOMATCH gas-turbine performance code [18] and MATLAB software. The following sections will describe the power requirements, power generated, and engine efficiency for LH₂ carrier ships in various conditions. The results of the preliminary design evaluation are listed in Table 3-3 [3].

Table 3-3 Ship parameters and power input data.

LH2 tanker parameter	Value	Unit
Class	JAMILA	-
Vessel type	LH ₂ Tanker	-
Total displacement (Δ_{total})	232000	tonnes
Lightweight (LWT)	210000	tonnes
Deadweight (DWT)	22000	tonnes
Length overall (LOA)	370	m
Length between perpendicular (LBP)	367.5	m
Length on the water line (L.W.)	367.9	m
Breadth Extreme (B)	75	m
Depth (D)	35	m
Draft (T) (full load condition)	10.012	m
Draft (T) (unload condition)	9.263	m
Block coefficient ($C_{B.}$) (full load condition)	0.819	-
Block coefficient ($C_{B.}$) (unload condition)	0.813	-
Ship speed (V)	18	knots
Midship Section area coefficient (C_m) (full load condition)	0.995	-

Midship Section area coefficient (C_m) (unload condition)	0.994	-
Waterplane area coefficient (C_{wp}) (full load condition)	0.900	-
Waterplane area coefficient (C_{wp}) (unload condition)	0.894	-
Prismatic coefficient (C_p) (full load condition)	0.824	-
Prismatic coefficient (C_p) (unload condition)	0.818	-
Displacement volume of the ship (∇)	226,342	m ³
LH2 cargo tank weight (Aluminium)	87,819 (21,955 x 4)	tonnes
LH2 cargo tank capacity	282,400(70,600 x 4)	m ³
LH2 cargo weight	20,000 (5000 x 4)	tonnes
LH2 engine fuel tank weight (Aluminium)	4,370	tonnes
LH2 engine fuel tank capacity	14,099	m ³
LH2 engine fuel weight (20 day return journey + 2-day ship idle period + 100 tonne reserve)	1278	tonnes
Boil off rate from the cargo	0.1 (20 tonne/day)	% per day
Fuel-saving percentage due to boiling off	29%	%
Voyage range	450 to 4,400	Naut mile
Minimum Propulsion Power Required	27.3	MW
Combined cycle gas & steam installed	50	M.W.

3.4 Power Requirements

As listed in Table 3-3, the estimation of the primary ship parameters [3] was followed by the investigation to establish the power plant requirements. From the outset, the authors decided to use a combined-cycle gas turbine as the prime mover for the LH₂ tanker ship to achieve high thermal efficiency with low NO_x signatures from the hydrogen gas turbines to satisfy the significant investments and efforts towards NO_x abatement [19]. Therefore, the authors selected a large-scale LH₂ carrier ship with a capacity of 280,000 m³ for suitability towards the global future energy demand [3]. Moreover, the hydrogen volume (280,000 m³) was divided into four tanks—each of 70,000 m³ capacity—with a total weight of 107,000 tons for all tanks, including cargo that assists the ship to maintain balance during the voyage. The speed of the LH₂ tanker was selected as 18 knots based on two primary reasons: the boil-off from the cargo rate, which was 0.1% per day during the voyage, and the maximum speed that can be achieved using the designed combined-cycle gas turbine with generated power in design point conditions. Furthermore, increasing the shipping speed will reduce the boil-off losses and increase the ship's fuel consumption; however, there is a maximum speed limit of 18 knots according to the engine design.

3.4.1 Resistance Prediction

In this section, the power required to achieve the service speed of 18 knots was estimated as the maximum design point speed. The calculations were initiated with a prediction of the total resistance of the JAMILA based on the shape and dimensions of the ship. In addition, the resistance and power of JAMILA were predicted using the Holtrop and Mennen method [14,15]. The total resistance can be estimated using the following equation [20].

$$R_T = R_F(1 + k_1) + R_{APP} + R_W + R_A + R_B \quad 3-1$$

where $R_F(1 + k_1)$ represents the viscous hull resistance, R_{APP} denotes the appendage resistance, R_W denotes the wave resistance, R_A indicates the model–ship correlation resistance, and R_B represents the additional pressure resistance of the bulbous bow near the water surface, which was assumed as zero owing to the ship design. Moreover, R_{TR} denote additional pressure resistance of the immersed transom stern, which was assumed to be zero due to the ship design.

3.4.1.1 Frictional Resistance (R_F)

The Reynolds number corresponding to the length of 368 m at the water line for the JAMILA is required to be evaluated.

$$R_n = \frac{V.L_W}{\nu}, \quad 3-2$$

where 1 knot is 0.5144 m/s, and the seawater kinematic viscosity (ν), according to the table in reference [21], was $1.1386 \times 10^{-6} \text{ m}^2/\text{s}$ for 15.0 C. The frictional resistance coefficient (C_F) can be calculated using the following equation.

$$C_F = \frac{0.075}{(\log R_n - 2)^2} \quad 3-3$$

The wetted surface area of the bare hull (S_{BH}) can be calculated with the following equation, where the transverse bulb area for JAMILA (A_{BT}) was 0 m owing to the design of the ship without a bulbous bow.

$$S_{BH} = L_W(2T + B)\sqrt{C_m} \left(0.4530 + 0.4425C_b - 0.2862C_m - \frac{0.003467B}{T} + 0.3696C_{WP} \right) + \frac{2.38A_{BT}}{C_b} \quad 3-4$$

The frictional resistance can be calculated based on the following equation [22].

$$R_F = \frac{1}{2} \cdot \rho \cdot C_F \cdot S_{BH} \cdot V^2 \quad 3-5$$

The following equation expresses the coefficient c accounting for the specific shape of the after-body. Although the JAMILA has a transom section stern shape, a normal stern shape was used for applying the correlations by Holtrop and Mennen [15]. As expected, the results did not cause large deviations. Thus, the form of the after-body coefficient (c_{stern}) was considered as 0.

$$c = 1 + (0.011 \cdot c_{stern}), \quad 3-6$$

and the length of the run (L_R) can be calculated using the following equation.

$$\frac{L_R}{L_W} = 1 - C_p + 0.06C_p \cdot \frac{lcb}{(4C_p - 1)} \quad 3-7$$

where lcb denotes the longitudinal position of the centre of buoyancy forward of $0.5L_W$ as a percentage (%) of L_W (+) for forward and (–) for afterwards. In this study lcb was 3.716. The form factor ($1 + k_1$) can be calculated using the following equation.

$$1 + k_1 = 0.93 + 0.487118c \left(\frac{B}{L_W}\right)^{1.06806} \left(\frac{T}{L_W}\right)^{0.46106} \left(\frac{L_W}{L_R}\right)^{0.121563} \left(\frac{L_W^3}{\nabla}\right)^{0.36486} (1 - C_p)^{-0.60247} \quad 3-8$$

3.4.1.2 Appendage Resistance (R_{APP})

The appendage resistance was evaluated based on the wetted surface area of the appendage (S_{APP}), appendage resistance factor ($1 + k_2$), and frictional resistance coefficient (C_F), wherein the following equation was used to approximate the values of ($1 + k_2$) as 2.8 and (S_{APP}) as 300 m² [15] that represent the azimuthal propulsors surface area.

$$R_{APP} = \frac{1}{2} \rho C_F S_{APP} V^2 (1 + k_2) \quad 3-9$$

3.4.1.3 Wave Resistance (R_w)

The Froude number of JAMILA can be calculated using the following equation:

$$F_n = \frac{V}{\sqrt{g \cdot L_W}}, \quad 3-10$$

where F_n was less than 0.4, and thus, the design was in the low-speed ship range. As the value of $\left(\frac{B}{L_W}\right)$ was 0.211, the value of C_7 was equal to that of $\left(\frac{B}{L_W}\right)$. The angle of the waterline at the bow (i_E) can be obtained using the following equation.

$$i_E = 0.1 + 89e^{\left[-\left(\frac{L_W}{B}\right)^{0.80856} \cdot (1-C_{Wp})^{0.30484} \cdot (1-C_p - 0.0225lcb)^{0.6367} \cdot \left(\frac{L_R}{B}\right)^{0.34574} \cdot \left(\frac{100V}{L_W^3}\right)^{0.16302} \right]} \quad 3-11$$

In addition, the value of C_1 can be calculated using the following equation, where $C_7 = \left(\frac{B}{L_W}\right)$ and

$$C_1 = 2223105 \cdot C_7^{3.78613} \cdot \left(\frac{T}{B}\right)^{1.07961} \cdot (90 - i_E)^{-1.37565}. \quad 3-12$$

The value of the coefficient that determined the influence of the bulbous bow on the wave resistance (C_3) can be calculated using the following equation.

$$C_3 = 0.56 \frac{A_{BT}^{1.5}}{[B \cdot T(0.31\sqrt{A_{BT}} + T_F - h_B)]} \quad 3-13$$

The value of the coefficient accounting for the reduction wave resistance caused by the action of a bulbous bow (C_2) can be calculated using the following equation. In the present case, the coefficient (C_2) equals one owing to the absence of a bulbous bow. Therefore, the value of the bulb area (A_{BT}) was zero. This value was used to calculate the coefficient that determined the influence of the bulbous bow on the wave resistance (C_3) (see Eq. 3-13), which was derived in the following equation.

$$C_2 = e^{-1.89\sqrt{C_3}} \quad 3-14$$

The value of the coefficient expressed the influence of a transom stern on the wave resistance (C_5) that can be calculated using the following equation, where A_T denotes the immersed part of the transverse sectional area of transom after perpendicular (A.P.) at zero speed as 700 m².

$$C_5 = 1 - \frac{0.8A_T}{B \cdot T \cdot C_m} \quad 3-15$$

As the value of C_p was greater than 0.8, the value of C_{16} was determined as

$$C_{16} = 1.73014 - 0.7067C_p. \quad 3-16$$

For the low-speed range, m_1 can be calculated as

$$m_1 = \frac{0.0140407L_W}{T} - \frac{1.75254 \nabla^{\frac{1}{3}}}{L_W} - \frac{4.79323B}{L_W} - C_{16}, \quad 3-17$$

where $(\frac{L_W^3}{\nabla}) = 239.78$ and is less than 512; $C_{15} = -1.69385$. Moreover, the value of m_4 can be calculated using the following equation.

$$m_4 = C_{15} 0.4e^{-0.034F_n^{-3.29}} \quad 3-18$$

As the value of $\frac{L_W}{B} = 4.9$, it is less than 12. Furthermore, the value of λ can be determined based on the following equation.

$$\lambda = 1.446C_p - \frac{0.03L_W}{B} \quad 3-19$$

Now the wave resistance can be calculated using the following equation, where (d) denotes a constant value of -0.9 .

$$R_w = \rho \cdot g \cdot \nabla \cdot C_1 \cdot C_2 \cdot C_5 \cdot \exp[m_1 \cdot F_n^d + m_4 \cdot \cos(\lambda F_n^{-2})] \quad 3-20$$

3.4.1.4 Model–Ship Correlation Resistance

The value of $(T_F/L_W) = 0.025 (< 0.04)$, where T_F is the fore draft assumed the same as the designed (T) draft. The value of $C_4 = 0.025$. The coefficient (C_A) can be calculated using the following equation.

$$C_A = 0.006(L_W + 100)^{-0.16} - 0.00205 + 0.003 \sqrt{\frac{L_W}{7.5}} C_B^4 C_2 (0.04 - C_4) \quad 3-21$$

The following equation can be used to calculate the model–ship correlation resistance.

$$R_A = 1/2 \cdot C_A \cdot \rho \cdot S_{BH} \cdot V^2 \quad 3-22$$

3.4.1.5 Total Resistance

The total resistance of JAMILA can be calculated as follows, and the output results of the resistance calculation will be presented in table 3-4

$$R_T = R_F(1 + k_1) + R_{APP} + R_W + R_A \quad 3-23$$

Table 3-4 Output results of the resistance calculation model for the LH2 tanker design.

Resistance calculation model parameters	Value	Units
Reynolds number (R_n)	3×10^9	—
Frictional resistance coefficient (C_F)	1.33×10^{-3}	—
Wetted surface area of the bare hull (S_{BH})	28500	m^2
Frictional resistance (R_F)	1671	kN
The specific shape of the afterbody coefficient (c)	1	—
The length of the run (L_R)	96.5 m	m
Form factor ($1 + k_1$)	1.32	—
Appendage resistance (R_{APP})	49.2	kN
Froude number (F_n)	0.1541	—
The angle of the waterline at the bow (i_E)	60.98	Degree
Coefficients values ($C_1, C_2, C_3, C_5, C_{16}$)	5.1, 1, 0, 0.19, 0.15	—
The values of m_1, m_4	$-1.85, -7.77 \times 10^{-8}$	—
Wavelength of the dynamic load case (λ)	1.04	—
Wave resistance (R_w)	94.2	kN
Correlation allowance coefficient (C_A)	3.311×10^{-4}	—
Correlation resistance (R_A)	390	kN
Total resistance (R_T)	2740	kN

3.4.2 Prediction of Propulsion Factors

The following method [15] was used to estimate the effective wake fraction (w), thrust deduction factor (t), and the relative rotational efficiency (η_R) of the twin-screw propulsion system designed for JAMILA, where D_{pr} denotes the propeller diameter and P/D_{pr} is the propeller pitch to diameter ratio estimated based on to the shallow draft and the propeller accommodation area as 6.4 m and 1.0, respectively. In this section, the C_B , C_p , and T were considered for the unloaded ship condition.

$$w = 0.3095C_B + 10[C_F(1 + k) + C_A]C_B - 0.23 D_{pr}/\sqrt{BT} \quad 3-24$$

$$t = 0.325C_B - 0.1885 D/\sqrt{BT} \quad 3-25$$

$$\eta_R = 0.9737 + 0.111(C_p - 0.0225.lcb) - 0.06325(P/D_{pr}) \quad 3-26$$

3.4.2.1 Power Prediction

The interactions between the hull and propeller for JAMILA can be calculated using an established method [23] as follows:

$$P_{EH} = R_T \cdot V, \quad 3-27$$

where P_{EH} denotes the effective horsepower for the ship hull. The open-water test of the propeller without a hull in front of it will produce a thrust T_H at a speed of advance V_A

with an open-water propeller efficiency (η_o), which can be calculated as the required thrust horsepower (P_{TH}) based on the following equations.

$$V_A = V(1 - w) \quad 3-28$$

$$T_H = R_T / (1 - t) \quad 3-29$$

$$P_{TH} = T \cdot V_A \quad 3-30$$

The hull efficiency (η_H) and the propulsive horsepower (P_{DH}) can be calculated using the following equation, where η_o denotes the propeller efficiency in open water, as presented in Tables 3-5 and 3-6, respectively.

$$\eta_H = (1 - w) / (1 - t) \quad 3-31$$

$$P_{DH} = P_{EH} / (\eta_H \cdot \eta_o \cdot \eta_R) \quad 3-32$$

Finally, the brake horsepower (P_{BH}) can be calculated using the following equation, where η_T is the transmission efficiency of the propulsion and was assumed as 0.99 [20].

$$P_{BH} = \frac{P_{DH}}{\eta_T} \quad 3-33$$

Table 3-5 Output results of the power prediction model for LH2 tanker design.

Power prediction model parameters	Value	Units
The effective wake fraction (w)	0.213	—
Thrust deduction factor (t)	0.218	—
Relative rotational efficiency (η_R)	99.2	%
Effective horsepower for the ship hull (P_{EH})	25.4	MW
A speed of advance (V_A)	7.28	m/s
Propeller thrust required (T_H)	3503.5	KN
The ship required thrust horsepower (P_{TH})	26	MW
The hull efficiency (η_H)	100.6	%
The propulsive horsepower (P_{DH})	45.5	MW
Brake horsepower (P_{BH})	46	MW

Figure 3-2 displays the output of the ship resistance and power calculations and their variation with the ship speed. Figures 3-2a–c depict the ship resistance, effective power, and power delivered to the propellers. Figure 3-2d portrays the brake power or the power delivered by the propulsion engines. For a ship speed of 18 knots in completely loaded condition, a delivered power of 48.5 MW is required to enable the sailing speed of 18 knots. In the worst-case scenario, labelled as OD1, a power of 30 MW. is

available in a high degradation case combined with a high ambient temperature. In this case, the ship's speed will be reduced to 16 knots. The details of D.P. and OD1 are described with the power plant analysis in Section 3.7.

Furthermore, Figures 3-2 show a minimal difference in the results between loaded and unloaded ship conditions owing to the cargo weight, which is 20,000 tonnes, very light compared with the ship's large size.

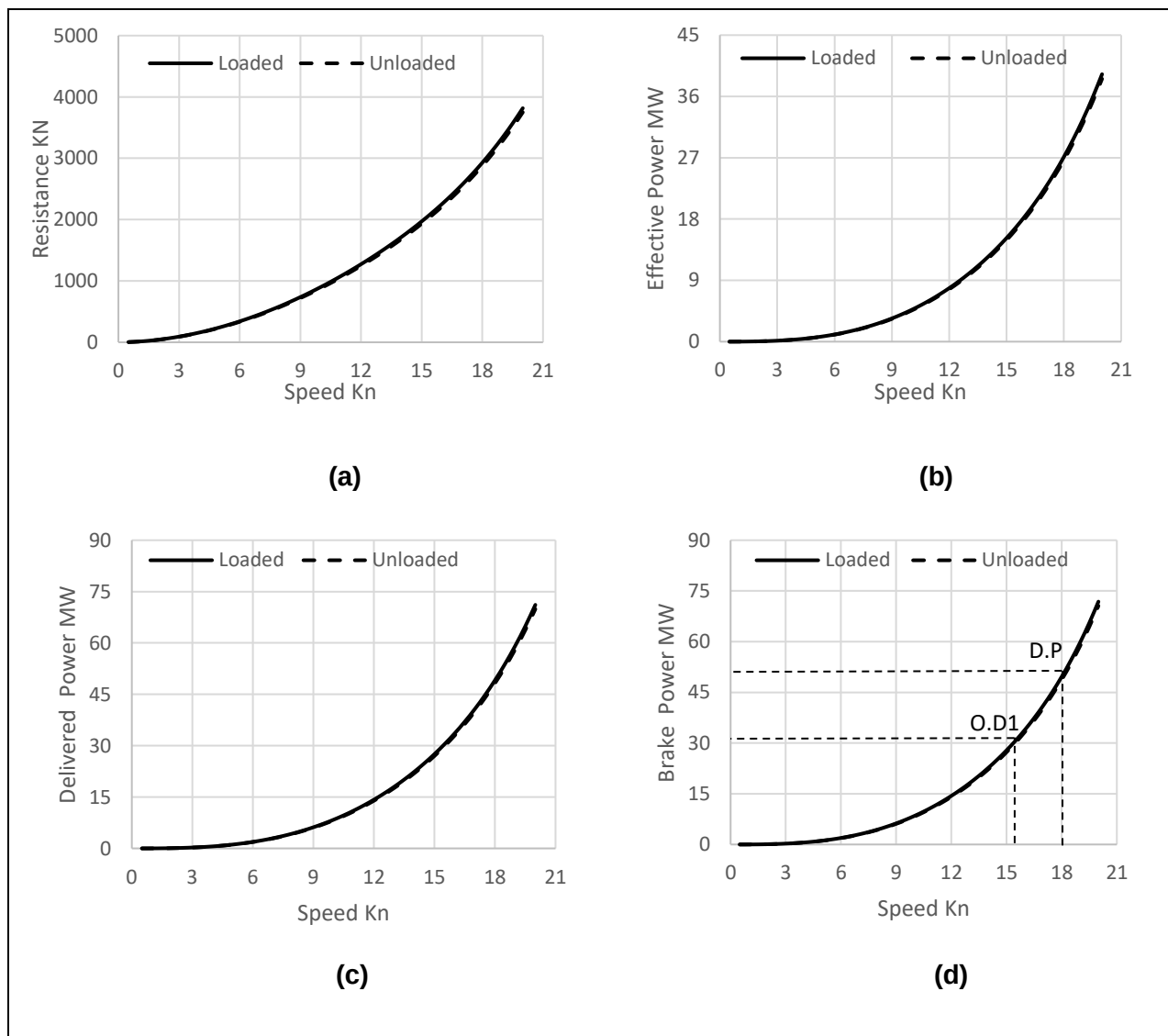


Figure 3-2 (a) Total resistance, (b) effective power, (c) delivered power, and (d) brake power estimated for the LH2 tanker for various speeds.

3.5 Open-Water Propeller Design and Characteristics

The authors opted for a fixed-pitch twin-screw propeller arrangement for the JAMILA tanker. This selection was guided by the ship speed and power requirement considering the size of the JAMILA and in line with the maximum allowable unloaded draft. Additionally, the authors examined the three- and four-bladed propellers. A four-bladed propeller was selected because the efficiency was 56% greater than that of the three-blade propeller (54%).

The design of the propeller was based on the open-water characteristics of the Wageningen B-series propellers [16]. Consequently, the propeller thrust (K_T) and torque (K_Q) coefficients were expressed as polynomials in the J , P/D_{pr} , A_E/A_O , Z , R_n , and t/c by the following equations.

$$K_T = f_1(J, P/D_{pr}, A_E/A_O, Z, R_n, t/c) \quad 3-34$$

$$K_Q = f_2(J, P/D_{pr}, A_E/A_O, Z, R_n, t/c) \quad 3-35$$

where J is an advance ratio, P/D_{pr} denotes propeller pitch diameter ratio, A_E/A_O represents the propeller blade area ratio, Z is the blade number, R_n is the Reynold number, and t/c denotes the thickness to chord length ratio. The main propeller design parameters can be shown in Table 3-6.

Table 3-6 Propeller design parameters and performance.

Propeller characteristic	Value	Unit
Propeller type	Fixed pitch	—
Number of blades (Z)	4	—
Number of propellers	Twin-screw fixed on the pods	—
Propeller diameter (D_{pr})	6.4	m
Pitch ratio (P/D_{pr})	1.0	—
Blade area ratio (A_E/A_O)	0.9	—
Advance coffined (J)	0.54	—
Wake Fraction (w)	0.213	—
Thrust deduction (t)	0.218	—
Thickness to chord length ratio (t/c)	0.029	—
Propeller rotating speed (n)	124.8	RPM
Propeller clearances and material	Value (for each propeller)	Unit
Clearance between propeller tip and hull	1.66	M
Clearance between propeller tip and keel	0.2	M
Propeller material	Ni-Al Bronze (NAB/ Nibral /Cu-3)	—
Propeller performance	Value (for each propeller)	Unit
Thrust Coefficient (K_T)	0.2528	—

Torque Coefficient (K_Q)	0.0418	—
Propeller thrust generated (T_{gh})	1852.6	KN
Propeller torque (Q)	311	KN.m
Open water efficiency (η_o)	56	%

The last stage of the propeller design was to investigate the non-cavitation criterion using the Aufer Keller equation.

3-36

$$A_E/A_O \geq K + \frac{(1.3 + 0.3Z) \cdot (T_h/2)}{D_{pr}^2(P_{atm} + \rho gh - P_v)}$$

$$A_E/A_O \geq 0.1 + \frac{(1.3 + 0.3 \times 4) \cdot (1752)}{(6.4)^2(101.366 + (1.025 \times 9.81 \times 3.4) - 1.704)}$$

$$A_E/A_O \geq 0.89,$$

where h denotes the value of shaft immersion depth, Z represents the propeller blade number, g is the acceleration due to gravity, P_{atm} is the atmospheric pressure, P_v denotes the vapour pressure of water and the value of $K = 0.1$ for twin-screw ships. However, the value of $A_E/A_O = 0.9$, which is the mean value for the propeller satisfying the cavitation test [20].

Figure 3-3 depicts the 3D design for the JAMILA fixed-pitch propeller that was designed using the Solid Work[®] design software. Explanatory, the black colour appears due to the choice of propeller blades material type, which is causes a surface reflection.

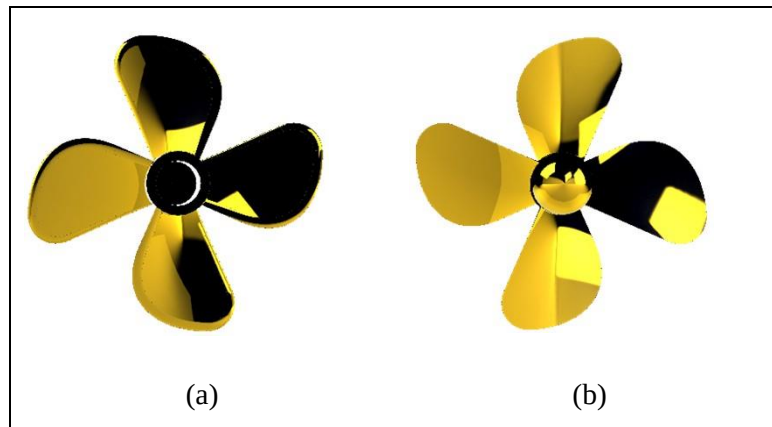


Figure 3-3 (a) Rear view of a four-blade propeller; (b) front view of a four-blade propeller.

3.6 Azimuthal-Podded Propeller Design

The propulsion system of JAMILA was designed as an efficient and applicable propulsion system owing to the large hull and small draft of the ship. The stern component of the LH2 carrier ship hull was designed with an unusual shape as compared with the conventional ships [3]. Consequently, this design allowed the authors to select the azimuthal thruster as a component of the LH2-carrier ship-propulsion system. This selection offered several solutions to achieve the optimum performance and logical design of the LH2-carrier ship-propulsion system in terms of accommodationist, manoeuvrability, reliability, and efficiency. In general, the azimuthal thruster propeller eradicated the shaft line, steering gear, rudder, and stern thrusters, which allowed to produce higher payloads at a greater speed for more effective operation with a smaller amount of energy from the power generators as compared with the usual axial propeller. Moreover, the azimuthal thruster exhibited brilliant manoeuvrability by offering full thrust in 360° operation, invisible noise and vibration, constant cruising speed, and substantial reduction of fuel consumption and GHG emission [24,25]. Specifically, in the case of the LH2 carrier ship, this selection caused the exclusion of the conventional inapplicable rudder from the designed LH2 ship owing to the shallow unloaded ship draft (9.263 m) [3]. The selection was based on the distance between the ship stern and keel, which was allowed limited accommodation of the designed dimensions for azimuthal pods, specifically for LH2 carrier ships. Moreover, the authors designed the system based on the Oasis-class cruise ship [26] in accordance with JAMILA power requirements. The JAMILA propulsion system comprised a turboelectric system including a combined-cycle gas turbine and azimuthal podded propeller of 50 M.W. The azimuthal-podded propeller pod propulsion design was inspired by XO2100, which was produced by ABB [27]. The design included two azimuthal-podded propellers with 15.5 MW maximum power output from each one. Figure 3-4 illustrates the primary components of the JAMILA turboelectric propulsion system. Moreover, the turboelectric propulsion system of the LH2 carrier ship included a single-pressure combined-cycle gas turbine as the primary mover to produce the required mechanical power, four generators, ten switchboards, two propulsion transformers, ten frequency convertors, two propeller motors located inside the azimuthal thruster case house. The efficiency of the system components assumed

optimal efficiency to achieve the propulsion power required and reducing the output power losses. Figure 3-5 presents the 3D design for the azimuthal-podded propeller system and propeller. Additionally, the specifications of the electric propulsion system will be presented in table 3-7.

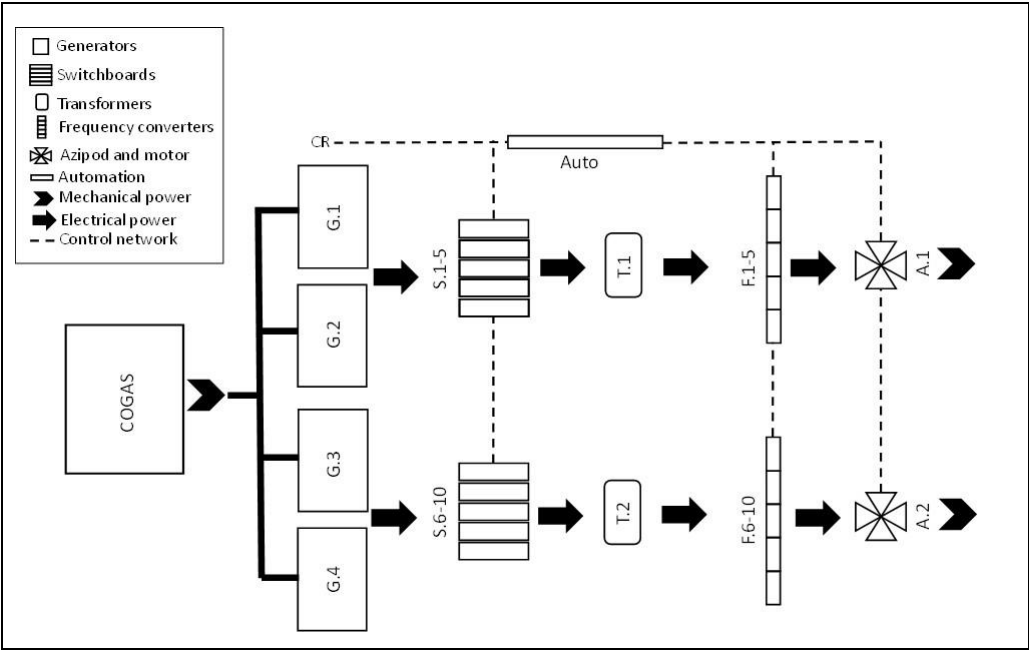


Figure 3-4 JAMILA Turbo-electric propulsion system components.

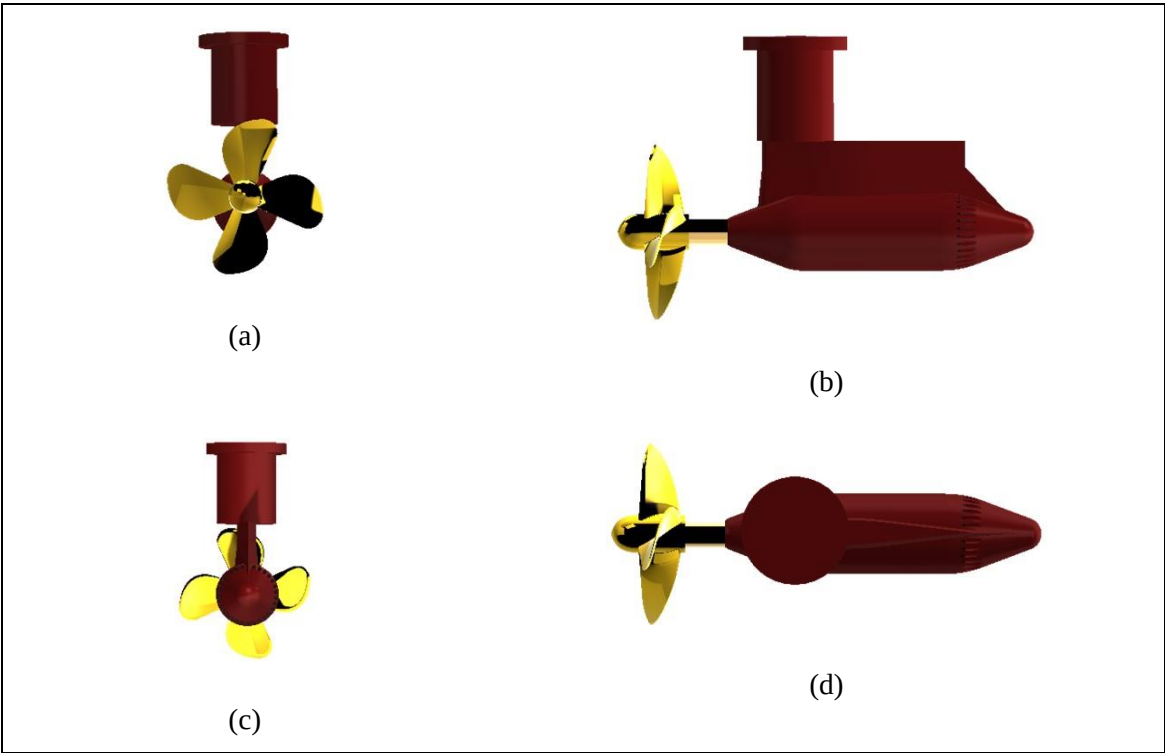


Figure 3-5 Turboelectric (a) front, (b) side, (c) rear, and (d) top views.

Table 3-7 General specifications of electric propulsion system.

Azimuthal podded propeller general specifications	Value (for each azimuthal podded propeller)	unit
Number of units	2	–
Total horizontal azimuthal podded propeller length	11.5	m
Total weight	280	t
Output power	15.5	MW
Main motor supply voltage	3000	V

3.7 COGAS Powerplant

The authors decided to incorporate the combined-cycle gas turbine using hydrogen fuel in the design to achieve the twin objectives of high efficiency and carbon footprint elimination. As a result, the total installed power output was slightly larger than the power estimated in Section 3.4. This condition provides a certain margin for conditions of high ambient temperature and gas turbine degradation. In addition, the gas turbine cycle was inspired by an existing advanced LM2500+ gas-turbine engine model that is frequently used for marine propulsion [28] and a single-pressure non-reheated steam cycle. The general specifications of the gas turbine and steam cycles are presented in tables 3-8 and 3-9, respectively. Subsequently, both design and off-design analyses were conducted considering the variations in ambient temperature and component degradation, as shown in Figure 3-6. The analyses were conducted using an in-house gas turbine performance software, TURBOMATCH using hydrogen as an alternative fuel and based on the gas turbine performance evaluation code [18] for conventional gas turbine performance [29].

Table 3-8 General specifications of gas turbine cycle.

Gas Turbine Cycle	Values	Units
Ambient temperature	288.15	K
Ambient pressure	101.3	kPa
Pressure ratio	23.1	–
Specific fuel consumption	0.0742	Kg/kw-h
Exhaust gas mass flowrate	84.948	Kg/s
Exhaust gas temperature	840.3	K
Turbine inlet temperature	1550	K
Fuel flow	0.7485	Kg/s
Power output	36.2	MW
Thermal Efficiency	40.3	%

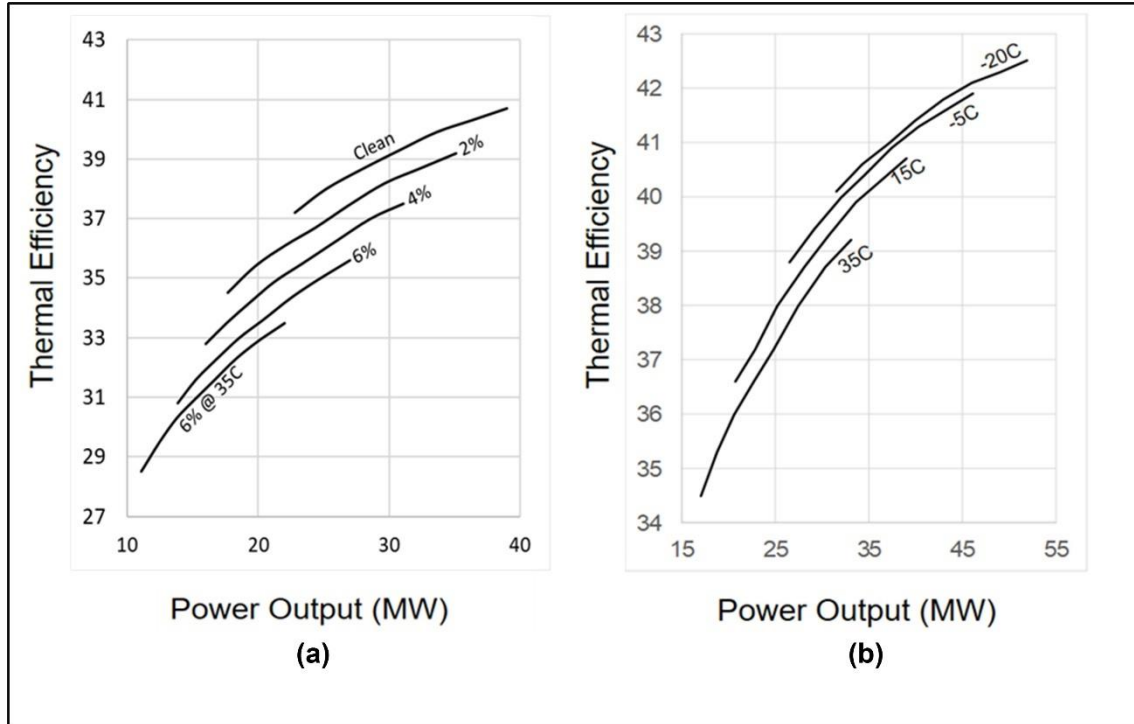


Figure 3-6 Gas turbine performance showing power output vs thermal efficiency (%). (a) Impact of degradation at a standard ambient temperature of 15 °C (Clean, 2%, 4%, and 6%) plus the influence of 6% degradation at an ambient temperature of 35 °C. (b) Gas turbine performance in clean conditions under the influence of ambient temperature.

Table 3-9 General specifications of a steam cycle

Steam plant parameters	values	units
superheat temperature (T_a)	559.8	C
Steam pressure (P_S)	60	Bar
Pinch point temperature difference (ΔT_p)	7.5	C
Approach point temperature difference (ΔT_a)	20	C
Steam mass flowrate (m_s)	10.51	Kg/s
Condenser pressure (P_{cond})	0.06	Bar
Feed water temperature (T_e)	36.2	C
Steam turbine output power (W_{ST})	14.35	MW
Steam turbine isentropic efficiency (η_{ST})	89.9	%
Pump work (W_{pump})	0.4139	MW

Figures 3-7 and 3-8 show the COGAS components with the single pressure HRSG and the heat recovery steam generator's heat transfer stages. However, the following model presents the combined-cycle performance calculation based on the following calculation steps [30,31].

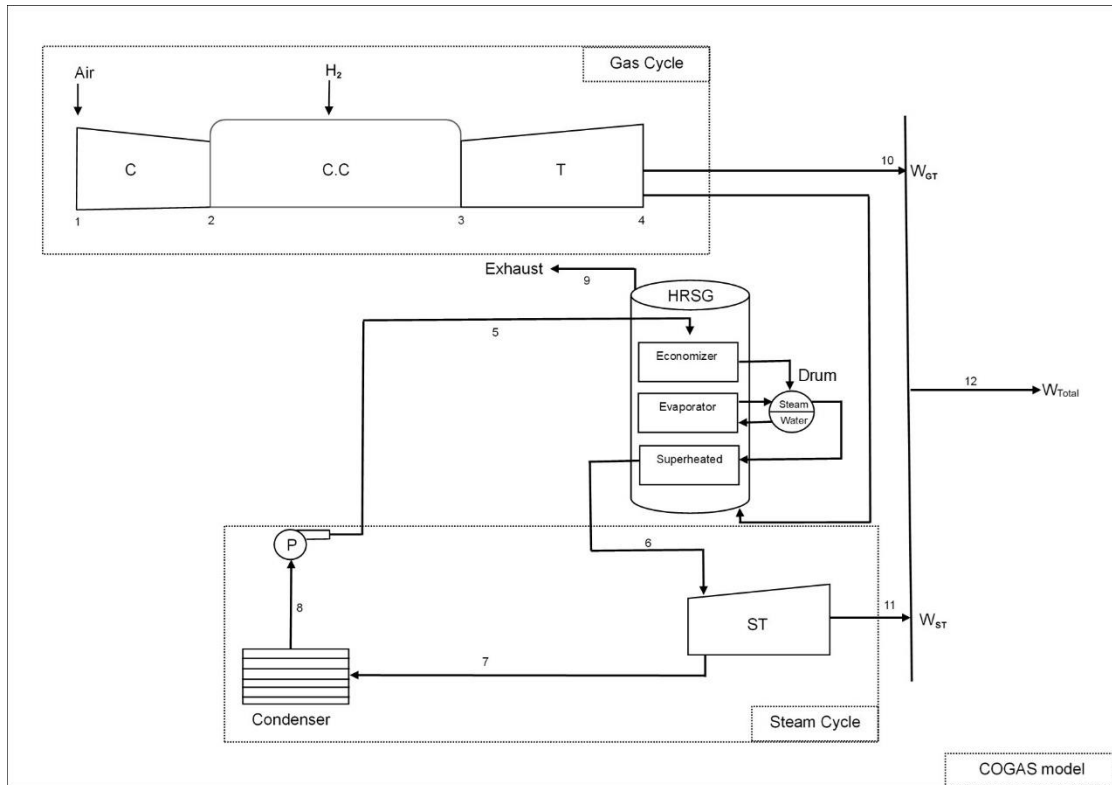


Figure 3-7 Combined cycle gas and steam turbine component. C: Compressor, CC: Combustor T: Turbine and S.T.: Steam Turbine.

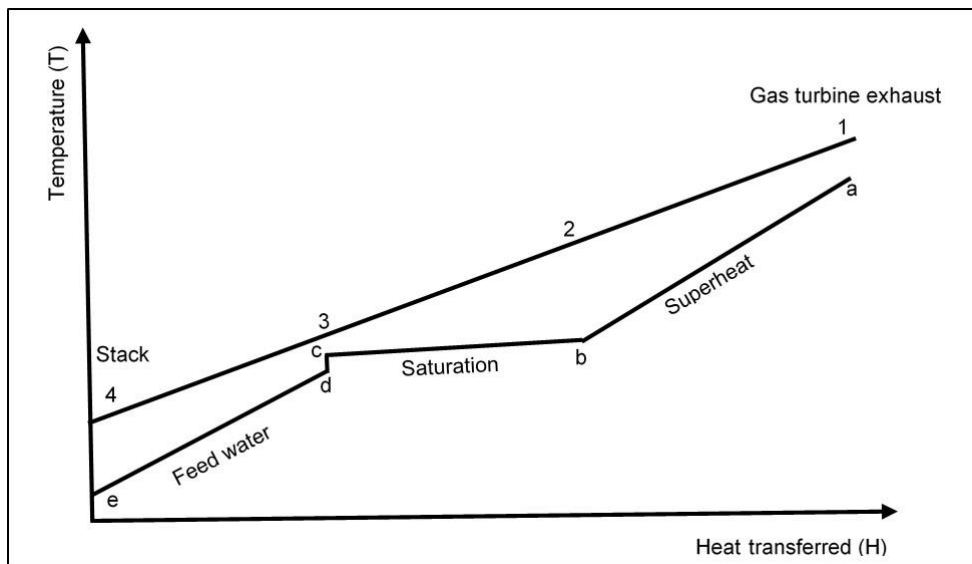


Figure 3-8 Heat transfer diagram for a single pressure HRSG.

The pinch-point temperature on the water side was calculated to determine the saturation relationship between pressure and temperature using the properties of fluid

tables. The steam pressure value of 60 bar was obtained from the saturated water and steam table.

$$T_c = T_b, \quad 3-37$$

where T_c and T_b are the saturation temperatures. The pinch-point temperature on the gas side (T_3) can be calculated using the following equation.

$$T_3 = T_b + \Delta T_p, \quad 3-38$$

where ΔT_p is the pinch-point temperature variation. The economiser outlet temperature (T_d) was simultaneously calculated using the following equation.

$$T_d = T_c - \Delta T_a \quad 3-39$$

The heat exchanged in the above-mentioned pinch point was determined using the following equation.

$$Q_{1-3} = m_g \cdot c_p \cdot (T_1 - T_3) \quad 3-40$$

where Q_{1-3} denotes the amount of heat captured by the water–steam circuit in the evaporator and superheater sections, so the following equation can be used with the water and steam enthalpy values to determine the steam mass flow. From the superheated steam table, 60 bar and 559.8 °C were selected for h_a , and from saturated water and steam table with respect to 60 bar for h_d [32].

$$m_s = \frac{Q_{1-3}}{h_a - h_d} \quad 3-41$$

The following equation was used to calculate the amount of heat exchanged under the pinch point and is expressed by the water-side energy balance (evaluate h_e using the saturated water and steam table for 36.2 °C).

$$Q_{3-4} = Q_{e-d} = m_s \cdot c_p (T_d - T_e) \quad 3-42$$

The following equation can be used to evaluate the Rankine cycle stack temperature.

$$Q_{3-4} = m_g \cdot c_p (T_3 - T_4) \quad 3-43$$

The following equations were used to determine the steam turbine expansion. Moreover, the superheated steam temperature and pressure were required to find the

steam turbine input enthalpy (h_i) and entropy (s_i), where $h_i = 3562.1 \frac{kJ}{kg}$ and $s_i = 7.05 \frac{kJ}{kg}$.

Furthermore, the condenser pressure (P_{cond}) is required to calculate the isentropic outlet steam quality (X) and the corresponding isentropic outlet steam enthalpy (h_{oiso}) and entropy (s_o), where $s_{og} = 8.329 \frac{kJ}{kgK}$, $s_{of} = 0.521 \frac{kJ}{kgK}$ and $h_{of} = 152 \frac{kJ}{kgK}$.

$$X = \frac{s_i - s_{of}}{s_{og} - s_{of}} \quad 3-44$$

$$h_{oiso} = X \cdot h_{ofg} + (1 - X) \cdot h_{of} \quad 3-45$$

$$h_{oact} = h_{oiso} + h_{of} \quad 3-46$$

The isotropic efficiency (η_{ST}) of the steam turbine was determined as

$$\eta_{ST} = \frac{h_i - h_{oact}}{h_i - h_{oiso}} \quad 3-47$$

The following equation was used to evaluate the steam turbine work (W_{ST}).

$$W_{ST} = m_s(h_i - h_o) \quad 3-48$$

$$W_{total_{ST}} = W_{ST} - W_{pump} = 14.3 - 0.4 = 13.9 \text{ MW} \quad 3-49$$

The Combined cycle total efficiency can be determined now by using the following equation.

$$W_{CC} = W_{GT} + W_{ST} \quad 3-50$$

$$\eta_{CC} = \frac{\eta_{GT} \cdot (W_{GT} + W_{ST})}{W_{GT}} \quad 3-51$$

The following table presented the output results of the COGAS model for liquefied hydrogen tanker design

Table 3-10 Output results of COGAS model for LH2 tanker design

COGAS model results	value	units
The saturation temperatures (T_c)	275.6	$^{\circ}C$
The pinch point temperature on the gas side (T_3)	283.1	$^{\circ}C$
Economiser outlet temperature (T_d)	255.6	$^{\circ}C$
Heat exchanged above the pinch (Q_{1-3})	24.7	MW
Steam mass flow (m_s)	10.51	kg/s

Heat transfer in gas side from HRSG (Q_{3-4})	2.7	MW
Rankine cycle stack temperature (T_4)	256	C
Outlet steam quality (X)	0.83	—
isentropic outlet steam enthalpy (h_{oiso})	2045	kJ/kg
Actual outlet steam enthalpy (h_{oact})	2197	kJ/kg
Steam turbine isotropic efficiency (η_{ST})	89.9	%
The steam turbine work (W_{ST})	14.36	MW
The total steam turbine work ($W_{totalST}$)	13.9	MW
Combined cycle total output power (W_C)	50	MW
Combined cycle total efficiency (η_{CC})	55	%

Figure 3-9 portrays the COGAS powerplant output power and thermal efficiency in design and off-design conditions obtained using MATLAB software.

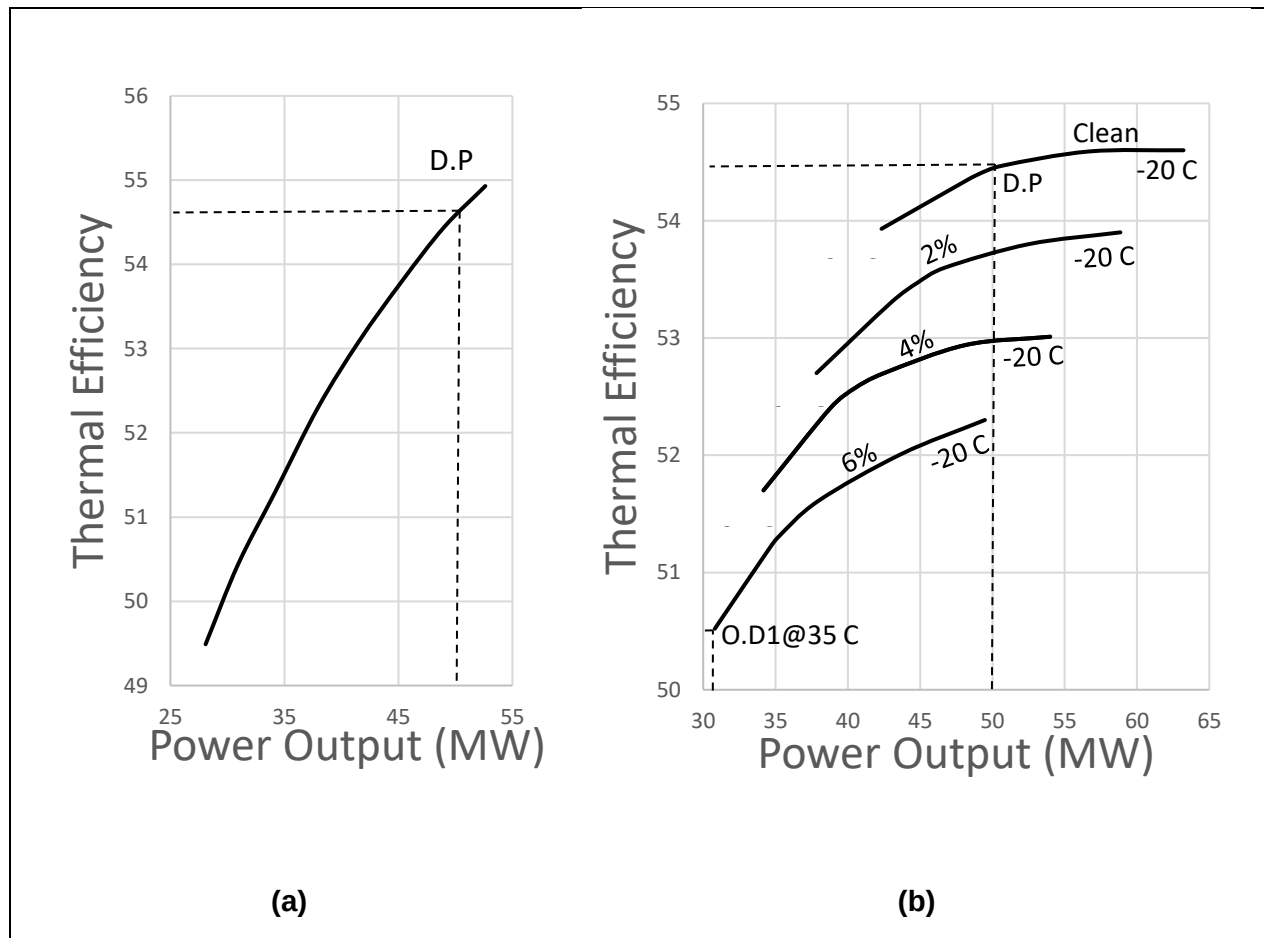


Figure 3-9 Performance depicting power output vs thermal efficiency (%). (a) COGAS performance according to Turbine Entry Temperature (TET) and clean conditions at an ambient temperature of 15° C. (b) COGAS performance according to ambient temperature and degradation.

The results presented in Figure 3-6a indicate that the output power of the gas turbine in design point was 36.2 MW at 15 °C and a TET of 1550 K. Additionally, the worst-case scenario of the gas-turbine output power was 20 M.W. at a turbine entry temperature of 1550 K and 6% degradation at 35 °C ambient temperature. Figure 3-2d illustrates that the required ship brake power was 49 M.W. at 18 knots for the design point and 31 M.W. at 16 knots for the off-design point under completely loaded conditions. Moreover, Figure 3-9a produce that the output power of the COGAS in the design point was 50 MW at 15 °C and a TET of 1550 K that's offer 13.8 MW as an additional generated power compared with the simple cycle gas turbine. For validation and error estimation, around 0.5% was found as an error percentage between simulation results and formal calculations of the COGAS additional power generated. Figure 3-9b depicts the total output power generated from COGAS was 50 M.W. at the design point and 31 M.W. in the worst-case scenario. The slight deviation between the total power generated from the COGAS propulsion system and the power required for JAMILA allows a small margin for degradation and ambient temperatures. Thus, the proposed COGAS design appears as a suitable option to power JAMILA at its design speed of 18 knots and at 16 knots under adverse weather conditions in a degradation sailing scenario.

Overall, the thermal efficiency of 50–54% can be achieved under the most recurring operating circumstances, which is highly considered for a marine power plant. This efficiency was not as high as that of a land-based gas turbine operating with combined cycles at typically 57–61% because the cycle is intended for application in marine duty, and therefore, it must not be aggressive. Nonetheless, the efficiency of the designed marine power plant was adequately high for practical purposes. Moreover, several factors reduce the thermal efficiency of the marine combined-cycle gas turbine, such as the small size of the gas-turbine components specifically for marine applications, sea-environmental effects, and the limitation of engine accommodation area onboard the ship [33,34]. However, a sizing exercise was not conducted in this study because the aft section of the ship was designed considering the characteristics of the Pulrose Power Station [35], which is familiar to one of the authors. Although this approach is not completely accurate, it provides confidence through a comfortable margin for the accommodation of the propulsion system.

3.8 Hydrogen Propulsion System Technical Feasibility

Evaluation of the suggested unique propulsion system fuelled by hydrogen in this study based on technical feasibility is essential for achieving the maritime zero-emission target by 2025. The research results show several advantages of the propulsion system, making this propulsion system suitable for the future, specifically for hydrogen carrier ships. These benefits are centred through the combination of technical aspects such as the system design philosophy, engine high thermal efficiency, zero CO₂ emission, perfect controllability, especially in shallow water and acceptable performance in design and off-design conditions compared with the current maritime propulsion systems. The following reasons show that the suggested propulsion system is feasible to apply in terms of the technical aspect.

- The results show that using a combined cycle gas turbine fuelled by hydrogen achieved 55% thermal efficiency with a zero CO₂-emission advantage compared with 54.5% using conventional fuel.
- The simulation results show that the combined cycle gas turbine fuelled by hydrogen has an acceptable thermal efficiency and power output performance to be a successful propulsion system in 6% of degradation under different weather conditions.
- The azimuthal thruster is the right choice causing exclusion of the conventional unapplicable rudder from the designed LH2 carrier ship due to the shallow unloaded ship draft (9.263 m). However, in the case of conventional maritime propulsion systems, the rudder is needed for the designed ship, which is an unlogic option due to the shallow ship draft, specifically in the liquefied hydrogen carrier ship.
- From an industrial point of view, the suggested maritime propulsion system fuelled by hydrogen is applicable and can be implemented with state-of-the-art techniques and tools [27][28].

3.9 Conclusion

This study determined the propulsion system characteristics of the JAMILA LH2 tanker. The power plant considered was a combined-cycle gas turbine, and the output design power was 50 M.W. The calculations suggested that ship requirement was 49

M.W. for 18 knots in case of completely loaded conditions in calm water. Subsequently, the simulation results suggested that this consideration was satisfied in a majority of the operational cases, even under conditions of degradation and increased ambient temperature. In the worst-case scenario of high degradation and ambient temperature, the proposed system still delivered 31 M.W. at a thermal efficiency greater than 50% allowing a ship speed of 16 knots.

Furthermore, the evaluation of the propulsion system identified the main features of the JAMILA, which was powered by a combined cycle to achieve an attractive thermal efficiency. Although a slightly more efficient power plant and propeller arrangement could be achieved with a detailed optimisation, the proposed system delivered a competitive performance and achieves the objective of presenting a visualisation of a potential LH2 tanker ship propulsion system.

ACKNOWLEDGEMENTS

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4 PAPER 3 - ECONOMIC ANALYSIS OF A ZERO-CARBON LIQUEFIED HYDROGEN TANKER SHIP

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Abstract

The green hydrogen economy is considered one of the sustainable solutions to mitigate climate change. This study provides an economic analysis of a novel liquified hydrogen (LH2) tanker fuelled by hydrogen with a total capacity of $\sim 280,000 \text{ m}^3$ of liquified hydrogen named 'JAMILA'. An established economic method was applied to investigate the economic feasibility of the JAMILA ship as a contribution to the future zero-emission target. The systematic economic evaluation determined the net present value of the LH2 tanker, internal rate of return, payback period, and economic value added to support and encourage shipyards and the industrial sector in general. The results indicate that the implementation of the LH2 tanker ship can cover the capital cost of the ship within no more than 2.5 years, which represents 8.3% of the assumed 30-year operational life cycle of the project in the best maritime shipping prices conditions and 6 years in the worst-case shipping marine economic conditions. Therefore, the assessment of the economic results shows that the LH2 tankers may be a worthwhile contribution to the green hydrogen economy.

Keywords:

Liquefied hydrogen; LH2 tanker; Hydrogen economy; Economic; Green economy; Tanker ship

4.1 Introduction

On 31st October 2021, the United Kingdom government hosted the 2021 United Nations Climate Change Conference (COP26) in Glasgow under the United Nations Framework Convention on Climate Change (UNFCCC) to implement the aim of the 2015 Paris Agreement to limit the global temperature increase to below 2.0 °C and to continuing the efforts to limit temperature increases to 1.5 °C [1]. To achieve these aims, there is a need to find an alternative to fossil fuels, which contribute greatly to CO₂ emissions. Green hydrogen can potentially be used as an alternative decarbonisation fuel for transportation, industrial, and power generation sectors as a solution to achieve a zero-emissions by 2050 and reach climate change targets [2]. Moreover, there is a global interest into hydrogen utilisation as an alternative to traditional fuel; for example, currently, annual hydrogen consumption in the European Union (EU) is approximately 9.7 million tonnes (Mt) and is expected to increase; the EU has the potential to generate approximately 2,250 terawatts per hour (TWh) of hydrogen by 2050 [3,4]. Currently, International Energy Agency (IEA) indicators show that yearly global hydrogen production is 120 Mt, representing approximately 4 % of the final consumption of international energy and other sectors [5,6]. Economically, the current cost of green hydrogen is approximately USD\$6/kg, which is considered a high cost due to the green hydrogen production costly electrolysis method using renewable energy sources (RES) [7,8]. However, by 2040, the cost is expected to decrease to USD\$2/kg due to a reduction in green hydrogen production prices and an increase in the number of countries exporting hydrogen [9,10].

Several countries have shown great interest in the investment in hydrogen technologies and utilisation; for example, in 2019, the Australian government committed to contributing approximately AUD\$500 million to subsidise clean hydrogen projects in different sectors according to the Australian national hydrogen strategy. In addition, the Australian government has declared an investment package of AUD\$70.2 billion for the activation of regional hydrogen export hubs [11]. Moreover, Canada supplies around 5 % of global hydrogen production markets, approximately more than 3.5 Mt per year and this capacity is expected to be 20 Mt by 2050, which will cover 30% of Canadas end-use energy [12,13]. Additionally, the “Green Flamingo” project expected investment of EUR\$57 billion by installing 1 GW of electrolysis capacity to support the green

hydrogen production and export it from Portugal to the Netherlands [14,15]. Chile has a commitment strategy to green hydrogen production and exportation using a clean renewable source. The Chile green hydrogen project expects to reach 25 GW of electrolysis by 2030 and export USD\$2.5 billion/year of green hydrogen and derivatives [15,16]. Moreover, Neom planned to create a large project to produce more than 600 tonnes of hydrogen daily by 2025, and to utilise green hydrogen as an environmentally friendly energy source to achieve a sustainable hydrogen economy in the future [17]. However, this very large demand for hydrogen is expected to require hydrogen to be transported by liquified hydrogen carrier ships. In this regard, there is a need to construct more than 500 large-scale hydrogen tankers to manage global hydrogen supply and demand [2]; hydrogen may be an economically efficient option based on the high demand and global supply.

Understanding the economic criteria of hydrogen carrier ships is essential as one of the promising options for large-scale transport of green liquid hydrogen in the future. This study analysed these aspects, which involved an advanced economic assessment of a large-scale liquified hydrogen tanker with a total capacity of 20,000 tonnes of liquified hydrogen. Previous related research focuses on the economic and design evaluation of large-scale liquified hydrogen carrier ships as an economical solution to shipping hydrogen overseas. In 1998, Abe et al. published an initial study of a preliminary design for a large-scale liquified hydrogen carrier ship with a total capacity of 200,000 m³ and a total cargo weight of 14,000 tonnes of liquified hydrogen; however, this study did not include an economic analysis for the large-scale liquified hydrogen carrier ship, which is essential to polarise the hydrogen investors companies [18]. In 2020, Boretti [19] investigated the hydrogen production likeliness from the excess renewable energy for export this hydrogen from Australia to overseas. The results indicated that Australia is challenging to produce and export hydrogen by excess wind and solar energy through electrolysis in the future. It will be more beneficial for Australia to develop its use of natural gas as a usable source for electricity generation [19]. However, the study only focused on the hydrogen production stage and did not consider the economic analysis of the hydrogen transportation technology as an energy carrier, which is considered a critical factor in the hydrogen exportation supply chain [19]. In 2020, Ishimoto et al. [20] evaluated the value chains of hydrogen transportation from Norway to markets in

Europe and Japan using liquified hydrogen and ammonia in terms of energy efficiency, environment, and cost of the different value chains. The economic aspect outcome showed that the liquification process and the difference in transportation distance play a significant role in the total cost level of hydrogen [20]. In 2021, Okunlola et al. [21] evaluated the cost to deliver gaseous hydrogen and export it from Canada to Asia, Europe, and North America. The delivery cost to those overseas destinations was evaluated using techno-economic analysis. The evaluation covered five stages of the supply chain: Hydrogen production using steam methane reforming method integrated with 52 % carbon capture, a long-distance inland hydrogen pipeline, liquefaction of hydrogen, hydrogen shipping, and finally, hydrogen regasification. The results showed that the supply chain costs of hydrogen for national stations in North America, Asia-Pacific, and Europe would be no more than CAD\$6.03/kg, CAD\$6.99/kg, and CAD\$8.14/kg, respectively [21]. In 2022, Johnston et al. [22] developed an open-source model to assess the shipping cost of different hydrogen carrier forms over different journeys to support the hydrogen suppliers and consumers. The assessment includes the transportation of liquid hydrogen (LH2), ammonia, liquefied natural gas (LNG), methanol and liquid organic hydrogen carriers (LOHCs). According to the study, the implementation of the evaluation took into account the port fees, possible canal usage charges, fuel costs, ship capital and operating costs, boil-off losses and possible environmental taxes. The results indicated that for Australia to Rotterdam and Australia to Tokyo journeys presented the same merit order of hydrogen carriers, with the cost reduction owing to shorter transportation distance. The results indicated that ammonia is the cheapest hydrogen carrier, followed by methanol, LNG and LOHCs, and LH2 as more expensive than other hydrogen carrier forms. In addition, Ingason et al. [23] developed an optimisation model to offer an optimal solution to achieve the most economical way for hydrogen production and transportation from Iceland to continental Europe. Heuser et al. [24] applied a techno-economic analysis method to investigate the cost of the green hydrogen supply chain produced from wind-powered-electrolysis between Patagonia and Japan. Wijayanta et al. [25] contrasted and assessed three different hydrogen carriers (liquefied hydrogen (LH2), methylcyclohexane (MCH), and ammonia (NH3)) by conducting a long-term cost prediction analysis. The results indicated that the ammonia with direct utilisation had been considered to have the

highest feasibility for massive adoption. If pure hydrogen is required as the end-use product, liquified hydrogen (LH2) could be a promising option as a carrier in the long run compared with other options. Brändle et al. [26] estimated the development of global production and supply costs of low carbon hydrogen from renewable energy sources and natural gas until the long term 2050. The analysis also evaluates the cost linked with the transportation of hydrogen using hydrogen carrier ships or pipelines. The results indicated that the green hydrogen produced from renewable energy sources could become an acceptable economic option in the coming years. By the long term 2050, the production costs for hydrogen from renewable energy sources could decrease to \$1.5/kg as a minimum production cost. Furthermore, owing to the high cost of seaborne transport using hydrogen carrier ships, the hydrogen pipeline networks could be the future solution to develop the hydrogen trade globally.

From previous studies, it is evident that there is a high potential of seaborne shipping as an effective method to export and import hydrogen between production and consumption countries due to the predicted high future demand for hydrogen. Therefore, there is a need to understand the economic feasibility of future large-scale liquified hydrogen tankers to accelerate the use of hydrogen to achieve climate change commitments. However, to the best of the authors' knowledge, the economic feasibility assessment of a large-scale liquefied hydrogen carrier ship fuelled by hydrogen has not been considered yet. Thus, the novel contribution of this research is to determine the complexity and quality of the economic aspects of a large-scale liquified hydrogen carrier ship as a viable option to support international governments and ship manufacturers to take action regarding the hydrogen economy. Therefore, this study's objective was to conduct an economic assessment of a large-scale liquified hydrogen carrier ship with a total capacity of 280,000 m³. In addition, the study addresses gaps in economic viability assessment in the long and short term for an actual-life use of the LH2 carrier ship as a major technology to contribute to the hydrogen economy supply chain.

4.2 Methodology

The following section describes the LH2 tanker ship economic assessment method based on established comprehensive economic analysis models [27]. The authors

extended and developed these models to analyse the economics of LH2 tanker ships with a total capacity of $\sim 280,000 \text{ m}^3$ as a promising future solution project to achieve a zero-emission target [2]. In this study, the authors assumed three scenarios for the liquified hydrogen carrier ship economic estimation. In the first scenario, ‘short-term 2020’, the hydrogen price is USD\$6/kg [7,8] and the hydrogen shipping price is USD\$1.2/kg [28]. The second scenario is ‘long-term 2040’, wherein the fuel price will decrease to USD\$2/kg [9], and the shipping cost will be the same as that in the short-term 2020 scenario. Finally, the third scenario, ‘long-term 2050’, assumes that the hydrogen cost is USD\$2/kg [9] and that the cargo shipping cost will decrease to USD\$0.7/kg from 2050 onwards due to the proliferation of hydrogen tanker ships which creates prices competition for hydrogen shipping.

4.2.1 Economic Evaluation Strategy

This study used a Business Model Canvas (BMC) as an effective strategic management tool to economically communicate, economically define, and assess the monetary costs and benefits of the LH2 tanker ship as a future promising green project. Table 4-1 shows the fundamental elements of the BMC used to estimate the economic feasibility of the LH2 carrier ship. In addition, the BMC describes capital, annual, emission, and investment costs, as these costs are considered essential to the economic analyses and envisioning future profits for the LH2 tanker ship project.

4.2.1.1 Essential Costs Description

The capital cost is defined as a one-time cost to start the business. The capital cost in this study was calculated based on: The weight of the ship hull, engine output power, and the number of Azimuthal pods as a part of the propulsion system; and hydrogen cargo, fuel tanks, and ship machinery costs as major elements for the LH2 tanker ship. However, the total capital cost in this study was assumed to be a constant cost for short and long-term scenarios due to the expectation of no change in primary component materials of the ship through the 30-year operational period.

The second cost is the annual cost: The yearly income of the project was estimated based on inflow and outflow costs calculations. In this study, the LH2 tanker ship inflow was confined to the cargo shipping cost, excluding the boil-off rate, which is 200

tons for each 20-day return journey [2]. Therefore, the variation in the shipping cost in each scenario will be the leading indicator to calculate the yearly income of the LH2 tanker ship. The outflow for the LH2 tanker ship project depends on fuel, boil-off from cargo tanks, emission taxes, and operation and maintenance costs. The main factor in the outflow cost is the variation in the hydrogen price, which will determine the fuel cost, and this cost is expected to decrease in the long term [9]. The crew cost was accounted for to estimate the total absolute annual income from the LH2 tanker ship.

The third cost is emission cost: Green hydrogen has been considered one of the leading solutions to achieve the maritime zero-emission target [29]; for this reason, the authors assumed that there are no emission taxes and penalties charged to the green hydrogen used in this study.

The fourth cost is an investment, i.e., the supplementary cost required to set up and run the project. In this study, this cost was employed to design, research, and develop the tanks and hull materials, and for the project consulting, manufacturing, supervision and engineering, contingency, and science and technology. The investment cost was calculated as an initial cost for the project, and this cost can be used for more than one version of the project because the same process will apply to all the versions from the same project. The authors assumed this cost would cover approximately 20 LH2 tanker ships in this study.

Table 4-1 Business model canvas for LH2 tanker ship

Capital cost ☐ LH2 cargo tanks ▪ Tanks materials ▪ Isolated materials. ▪ Tank structures. ▪ LH2 pipeline ▪ LH2 tanks accessories and equipment's ☐ Hull construction ▪ Materials ▪ Super structure ☐ COGAS ▪ Gas turbine LM2500+ ▪ Single pressure HRSG ▪ Steam turbine ▪ Condenser ▪ Pump ▪ Electric generators ☐ Azimuthal pods ▪ Four blades propeller ▪ Electric cables ▪ Electric Motors ▪ System equipment's ☐ Ship machinery and systems	Annual cost ☐ Inflow ▪ Cargo shipping ☐ Outflow ▪ Maintenance ▪ Operation ▪ Fuel cost ▪ Boil off from cargo tank ▪ Emission tax	Emission cost ☐ NOx	Economic analysis ☐ Payback period ☐ Net present value ☐ Internal rate of return ☐ Profitability index ☐ Economic added value
Investments cost ☐ Manufacturing costs ☐ Engineering and supervision ☐ Consulting and contingency ☐ Science and technology ☐ Research and development		Revenue ☐ Operation distance ☐ Fuel cost ☐ Cargo Boil off ☐ Maintenance cost ☐ Emission cost	

4.2.1.2 Economic Analysis Explanation

BMC involves four effective tools to assess the LH₂ tanker ship toward ensuring the economic feasibility of the project. Those tools represent the central key role of the economic analysis for short and long-term scenarios. The leading four tools are as follows.

- Net present value (NPV) is one of the primary metrics in finance in the industrial sector and is applied to the cash flow of a project to evaluate the current and future industrial investment projects [27,30]. Therefore, a low NPV signifies a critical financing indicator to the enterprise, ensuring project loss and vice versa. Furthermore, economically, a negative NPV leads the investor to reject the project, especially when the NPV value is lower than the project initial investment amount; conversely, the investor will accept the positive NPV when the NPV is higher than the initial investment expenditure [27]. Therefore, this research applied the NPV for LH₂ tanker ships as a promising project through three scenarios. Furthermore, for increased accuracy, the authors examined the

influence of the discount rate on the NPV value; this rate was assumed to be constant at 4 % for each scenario through 30 years as a project operation life cycle [30]. Therefore, as a critical metric for this project, the NPV can be calculated using Equation 4-1 [31], where X_t is the future net cash flows, R is the average periodic rate to invest, and t, n is a time.

$$NPV = \sum_{t=0}^n \frac{X_t}{(1 + R)^t} \quad 4-1$$

- Internal rate of return (IRR) is a method used to evaluate the project capability to achieve investor trust, and is defined as the stage when the project NPV equals zero. The criterion for acceptance of the project depends on the IRR percentage relative to the discount rate; if the IRR percentage is higher than the discount rate, the investor will accept the project and the investment is considered profitable. This method was applied in this study over 30 years for each scenario for the LH2 tanker ship to estimate the different IRR percentages. In addition, the estimation included the extended internal rate of return (XIRR) by using specific dates to obtain the estimation accuracy. Equation 4-2 was applied to calculate the IIR [32], where C_t is the future cash flow, IRR is the internal rate of return, and t, n is the total period.

$$\sum_{t=0}^n \frac{C_t}{(1 + IRR)^t} = 0 \quad 4-2$$

- The payback period (PP) is the tool representing the required operational period of the project to cover the initial business investment. The criteria to evaluate the project using this tool are established as follows: A low PP indicates that the investor will accept the business due to the high-profit achievability; conversely, a high PP means that the project is non-profitable [27]. In this study, the PP depended on the total yearly absolute income from carrying liquified hydrogen and the influence in the hydrogen shipping prices in the long term. Equation 4-3 was applied to calculate the PP, where I_o is the initial investment and C_a is the net annual cash inflow [27].

$$PP = \frac{I_o}{C_a} \quad 4-3$$

- Economic value added (EVA) is a method used to estimate the economic profit of projects in large-scale business sectors. A project with a higher EVA is usually more efficient than one with a lesser EVA. In addition, this tool can compare the efficiency of more than one project to differentiate between projects in the event of multiple investment options [33,34,35]. This tool is effective for the LH2 tanker ship due to the differences in the hydrogen and shipping prices over 30 years. This method was applied for each scenario with a 10-year period, changing the percentage of the weighted average cost of capital (WACC) for each scenario to determine the period of the highest EVA value. Equation 4-4 was used to estimate the EVA, where *NOPAT* is the net operating profits after tax and *WACC* is the weighted average capital cost.

$$EVA = NOPAT - (WACC \times Capital\ investment) \quad 4-4$$

4.2.1.3 Case Study

The authors collected the JAMILA hydrogen carrier ship data from authentic published sources [2] to create the economic assumptions for the hydrogen carrier ship as follows:

1. The cost of liquified hydrogen cargo and boil-off per tonne is USD\$6/kg based on the European Commission July 2020 hydrogen strategy [7] for the short-term scenario and USD\$2/kg for long-term 2040 and 2050 scenarios [9], whereby the cargo is assumed to be green hydrogen. The total cargo weight includes 0.1 % of boil-off, i.e., 20,000 tonnes, which will cost a USD\$120,000,000/voyage for the short-term scenario and USD\$40,000,000/voyage for long-term scenarios. Furthermore, the authors assumed that the ship was designed with an average speed of 18 knots to operate for 20 days as a maximum period for a return journey based on a previous study [2], equating to 12 journeys per year; in this case, the cargo will have a total cost of USD\$1,440,000,000/year in the short-term and USD\$480,000,000/year in the long-term, including boil-off, as a total yearly cargo price.
2. 30-years lifetime operational hours for the JAMILA ship have been appointed until its retirement.

3. Based on a previous study [36], the crew cost is USD\$1,460,000/year established on the Very Large Crude Carrier (VLCC) crew size.
4. The authors assumed that the income cash flow is constant for the entire 30-year operation of the JAMILA ship.
5. The emission taxes and charges were neglected in this study due to the low NO_x emission produced by the hydrogen carrier ship [37].
6. The ship was designed to consume around 2.87 t/hour of green hydrogen fuel, which costs USD\$17220/hour for a short-term scenario. This cost includes 0.1 % of boil-off, representing 0.83 t/hour from the cargo tanks. Therefore, the total fuel consumption is assumed to be 16531.2 tonnes/year, with a fuel cost of USD\$99,187,200/year [38]. For the long-term period, the ship fuel cost will be USD\$5740/hour, including the boil-off from the cargo tanks; consequently, in this case, the total fuel cost per year is assumed to be USD\$33,062,400/year [38].
7. Some data was calculated based on the liquified natural gas (LNG) carrier ships due to the global limitations in hydrogen carrier ship designs [39].
8. The cost of LH₂ cargo and prime mover fuel tanks is assumed to be USD\$30/kg [40,41], which is a total cost of USD\$600,000,000 based on hydrogen carrier ship design [2,40]. This amount is assumed to decrease in the long-term period and is estimated to be USD\$200,000,000/ship.
9. The investment cost for design, research, and development of the tanks and hull materials, manufacturing, engineering and supervision, consulting, and contingency, science and technology is estimated to be USD\$41/kg [40], which equates to USD\$820,000,000.00 as a total investment cost (assumed for a class of 20 ships).
10. The cargo shipping cost is assumed to be USD\$1.2/kg for the short-term 2020 and long-term 2040 scenarios [28], and the authors assumed that the cargo transportation price would decrease to USD\$0.7/kg in 2050.

4.3 Results and Discussion

The economic assessment results and cost details for the JAMILA LH₂ tanker ship are presented in this section based on the BMC, shown in Table 1. In terms of the capital

cost of the JAMILA LH2 tanker ship, which is presented in Table 4-2, the results show that the LH2 cargo and engine fuel tank costs have the most significant effect on the LH2 tanker ship capital cost due to the liquified hydrogen tanks specifications, such as high insulation requirements and high material weights compared with the conventional liquid cargo tanks. It is assumed that this cost will decrease in the long-term period, which will positively affect the economic efficiency of the ship in the future. However, LH2 cargo and engine fuel tank costs need to be considered in the stages of developing, manufacturing, and material cost calculations. Moreover, the ship hull cost is classified as the second-highest cost that falls under the capital cost estimation due to the increase in the hull weight, which is 51,334 tonnes, compared with the conventional tanker ships in similar dimensions of the LH2 tanker ship. This high weight helps to achieve ship stability requirements and increases the hull efficiency to safely carry the liquified hydrogen tanks. This analysis revealed that the total capital cost of an LH2 tanker ship with 20,000 tonnes of liquified hydrogen capacity is approximately USD\$480,818,160, which is acceptable compared to that of an LNG carrier ship of a similar size.

The next part of the economic evaluation involved a cash flow estimation for the JAMILA ship. The results showed that the difference in the liquified hydrogen price does not affect the LH2 ship total inflow. However, economically, it was observed from the cash flow results that the shipping cost plays a significant role in the inflow estimation. Table 3 shows the negative effect in the inflow in the long-term 2050 scenario due to decreased shipping cost; this effect decreased the inflow value from USD\$23,760,000/journey to USD\$13,860,000/journey for 19800 tonnes of liquified hydrogen as a whole load cargo (excluding 200 tonnes boil off) for a 20-day return journey.

Moreover, the outflow estimation for the same scenarios was calculated based on fuel cost, boil-off from cargo tanks, and operation and maintenance costs. In this case, the liquified hydrogen price will significantly affect the outflow amount of the LH2 tanker ship. Table 3 shows that the total outflow cost in the long-term 2040 and 2050 scenarios is less than half the cost in the short-term 2020 scenario, due to the reduction in the liquified hydrogen price by 2040, which has a positive effect on total outflow due to the decrease in the costs of fuel and the liquified hydrogen boil-off from the tanks in case of

the long-term 2040 and 2050 scenarios. Additionally, Table 4-3 shows that the total 30-year income for 12 journeys/year in the long term 2040 scenario is USD\$6,509,928,000, which is higher than that of the short-term 2020 and long-term 2050 scenarios. This due to the hydrogen price, which is USD\$2/kg compared with USD\$6/kg in the short-term 2020 scenario, and the hydrogen shipping cost which is USD\$1.2/kg compared with USD\$0.7/kg in the long-term 2050 scenario. Therefore, based on the cash flow results, to achieve the optimum income from the LH2 tanker ship, there is a need to lower hydrogen prices and maintain shipping costs.

Table 4-2 Estimated LH2 carrier ship capital cost

JAMILA LH2 carrier ship capital cost			
Item	Cost	Unit number	Total cost (USD\$)
Ship hull and super structure construction	3.49 USD\$/kg [39]	51,334,000 kg [2]	179,155,660
Combined cycle gas turbine (COGAS)	26,500,000 USD\$[42]	50MW–LM2500 GOGAS [2,38]	26,500,000
Azimuthal pods electrical propulsion system	15,000,000 USD\$ [43]	15.5 MW each of two azimuthal-podded propellers [38]	30,000,000
Ship machinery and equipment's	15USD\$/m ³ of LBT [39]	LBT is 277,500 m ³ [2]	4,162,500
LH2 cargo and engine fuel tanks (long-term falling \$200,000,000 per ship) based on:	30 USD\$/kg [40,41]	20,000,000 kg [2]	200,000,000
• Wall material (Aluminium 4.4% Cu) • Insulation foam (Rigid closed-cell Polyurethane) • Liner alloy (Aluminium 5086) • Construction outlay • LH2 storage system and equipment			
Total capital cost			439,818,160
Investment cost (for a class of 20 ships)	41 USD\$/kg [40]		41,000,000 (for each ship)
Total			480,818,160

Table 4-3 Estimated LH2 carrier ship cash inflow and outflow

JAMILA LH2 carrier ship cash flow estimated for 20-day return journey				Units
Inflow	Short term (2020)	Long term (2040)	Long term (2050)	-
Cargo shipping (19,800 tonnes) [2]	1.2 [28]	1.2 [28]	0.7	USD\$/kg
Total inflow	23,760,000	23,760,000	13,860,000	USD\$/ Journey
Outflow	Short term (2020)	Long term (2040 and 2050)		-
Fuel (1,377.6 tonnes – 200 tonnes boil off) [2]	6 [7] (–7,065,600)	2 [9] (–2,355,200)		USD\$/kg (USD\$/ Journey)
Operation and Maintenance (20,000 tonnes) [2]	1.7 [44] (–2,800,000)	1.7 [44] (–2,800,000)		USD\$/kg per year (USD\$/ Journey)
Boil off from cargo tank (200 tonnes) [2]	6 [7] (–1,200,000)	2 [9] (–400,000)		USD\$/kg (USD\$/ Journey)
Emission tax	0	0		USD\$/Journey
Total outflow	–11,065,600	–5,555,200		USD\$/ Journey
Period	Short term (2020)	Long term (2040)	Long term (2050)	-
Total income	12,694,400	18,204,800	8,304,800	USD\$/Journey
Yearly income (12 journeys/year)	152,332,800	218,457,600	99,657,600	USD\$/year
Crew cost	–1,460,000	–1,460,000	–1,460,000	USD\$/year
Absolute total yearly income	150,872,800	216,997,600	98,197,600	USD\$/year
Absolute 30-year income	4,526,184,000	6,509,928,000	2,945,928,000	USD\$

The cash flow results are one of the keys to estimating the NPV for the JAMILA LH2 tanker ship. Table 4-4 shows the NPV calculations for each scenario to estimate the amount of profitability realised by investing in the JAMILA ship for 30 years. The authors assumed that the discounted rate for each scenario was 0.4 % [30], and the range of the discount factors for a 30-year period is from 0.96 % over the first year to 0.31 % for the last year. The results indicated that in the long-term 2050 scenario with a discounted value of 4 %, the lowest NPV with the amount of USD\$1,698,036,169 is acceptable compared with the other scenarios. Therefore, this NPV gain from the large scale LH2 tanker ship project shows that the investment is acceptable. The long-term 2040 scenario achieved the highest present value of USD\$3,752,329,725 with the same discounted value; however, this achievement is due to the high yearly income cash flow.

Table 4-4 JAMILA ship net present value (NPV)

NPV	Short term (2020)	Long term (2040)	Long term (2050)	Units
Discount rate	4.0 [30]	4.0 [30]	4.0 [30]	%
Number of years	1–30	1–30	1–30	Year
Discount factor	0.96–0.31	0.96–0.31	0.96–0.31	%
Undiscounted cash flow	\$150,872,800	\$216,997,600	\$98,197,600	\$USD/year
Present value	\$145,070,000– \$46,516,901	\$208,651,538– \$66,904,411	\$94,420,769– \$30,276,153	\$USD/year
NPV	\$2,608,897,482	\$3,752,329,725	\$1,698,036,169	\$USD
Value of the discount	\$5,802,800– \$104,355,899	\$8,346,062– \$150,093,189	\$3,776,831– \$67,921,447	\$USD/year

The IRR for the LH2 tanker ship was employed to assess the potential profitability of the investment. Then, the IRR was applied to determine the precise discounted percentage needed for the cash flow of the project to realise an NPV of zero. Table 4-5 presents the IRR percentages of the LH2 tanker ship for 30 years (as the estimated lifetime of a ship) for the evaluated scenarios. The results showed that the highest IRR is 45.13 % in the long-term 2040 scenario (compared to 20.25 % in the worst-case scenario, i.e., the long-term 2050 scenario). The IRR percentage for the worst-case scenario can achieve the high potential of low-risk investment. This IRR of the project achieved a very high and unusual percentage; this achievement is due to the yearly income of the project being very high compared with the total capital cost of the project.

Table 4-5 JAMILA ship internal rate of return (IRR)

Period	1–30 years	Short term (2020)			Units
IRR	31.37%	Year 1	Each year	Year 30	Year
		-480,818,160	150,872,800	150,872,800	\$USD/year
Period	1–30 years	Long term (2040)			Units
IRR	45.13%	Year 1	Each year	Year 30	Year
		-480,818,160	216,997,600	216,997,600	\$USD/year
Period	1–30 years	Long term (2050)			Units
IRR	20.25%	Year 1	Each year	Year 30	Year
		-480,818,160	98,197,600	98,197,600	\$USD/year

The authors estimated the XIRR for the LH2 carrier ship using specific dates to obtain precise calculations. Table 4-6 shows the IRR from 28/06/2025 to 30/12/2053 for each year in short and long-term scenarios. The results showed that the XIRR for the LH2 carrier ship in the long-term 2040 scenario is 56.26 %; conversely, in the long-term 2050 scenario, the percentage is 22.50 % which offers an acceptable value for investors to maintain the successful operation of the project.

Table 4-6 JAMILA ship extended internal rate of return (XIRR)

Period	1–30 years	Short-term (2020)			Units
XIRR	36.59%	28/06/2025	Each year	30/12/2053	Year
		- 480,818,160	150,872,800	150,872,800	\$USD/year
Period	1–30 years	Long-term (2040)			Units
XIRR	56.26%	28/06/2025	Each year	30/12/2053	Year
		- 480,818,160	216,997,600	216,997,600	\$USD/year
Period	1–30 years	Long-term (2050)			Units
XIRR	22.50%	28/06/2025	Each year	30/12/2053	Year
		- 480,818,160	98,197,600	98,197,600	\$USD/year

To estimate the period needed for the cost of the project investment to be covered, we applied the PP assessment method. Tables 4-7a–c shows the PP for LH2 tanker ship investment from years 0–30. The short-term 2020 scenario does not need more than 3.5 years to cover the LH2 tanker investment. In the case of the long-term 2040 scenario, the PP is not more than 2.5 years, representing a short period compared with that of other projects due to the high NPV and the IRR. However, this is profitable, considering

that less than 2.5 years of the project running life cycle represents 8.3% of the assumed 30-year operation of the LH2 tanker ship. Finally, in the long-term 2050 scenario, the results in Table 4-7c show that the PP is approximately 6 years, representing 20% of the project's operational period; however, it is still acceptable compared with other investments.

Table 4-7 JAMILA ship payback period (PP)

PP (a)	Short term (2020)			Units
Investment	Year 0	Each year	Year 30	Year
Cash flows	\$480,818,160	\$150,872,800	\$150,872,800	\$USD/year
PP = \$480,818,160/\$150,872,800 = 39 Months				
PP (b)	Long term (2040)			Units
Investment	Year 0	Each year	Year 30	Year
Cash flows	\$480,818,160	\$216,997,600	\$216,997,600	\$USD/year
PP = \$480,818,160/\$216,997,600 = 27 Months				
PP (c)	Long term (2050)			Units
Investment	Year 0	Each year	Year 30	Year
Cash flows	\$480,818,160	\$98,197,600	\$98,197,600	\$USD/year
PP = \$480,818,160/\$98,197,600 = 59 Months				

From a financial performance perspective, the economic evaluation of the LH2 tanker ship sustainability was based on the EVA. This method indicates the economic value contribution of the LH2 tanker ship for the future. Therefore, it is essential to establish the investment cost per year that is expected to apply EVA and sustain the LH2 tanker ship project. Table 4-8 shows the investment cost required for the project per year, including fuel, crew, maintenance, and operation costs. It is noticeable that the fuel cost is the primary factor in the investment cost estimation for LH2 tanker ships. Table 8 shows that the total investment cost for the project in the short-term 2020 scenario is USD\$119,847,200/year, which is higher than that for the long-term 2040 and 2050 scenarios (USD\$63,322,400/year). The variation of hydrogen price is the main reason for the difference in total investment cost for each scenario. The following assumptions were made to support the EAV estimation:

- The tax rate on LH2 shipping using tanker ships as income is zero.
- The WACC is assumed based on a calculation to be 5–6 % with a percentage of 0.5 as an annual increase [45].
- The net operating profits after tax (NOPAT) are assumed as follows:
 - NOPAT for short-term 2020 = USD\$150,872,800.

- NOPAT for long-term 2040 = USD\$216,997,600.
- NOPAT for long-term 2050 = USD\$98,197,600

Table 4-8 JAMILA ship investment cost

Investment cost	Short term (2020)	Long term (2040 and 2050)	Units
Fuel cost	84,787,200 [2,7]	28,262,400 [2,9]	\$USD/year
Crew cost	1,460,000 [36]	1,460,000 [36]	\$USD/year
Operation and maintenance costs	33,600,000 [44]	33,600,000 [44]	\$USD/year
Total cost	119,847,200	63,322,400	\$USD/year

Table 4-9 shows that the highest EVA values for the short-term 2020, long-term 2040, and long-term 2050 scenarios are USD\$144,281,204.00, USD\$213,514,868.00, and USD\$94,714,868.00, respectively. The differences in EVA in each scenario are based on the finance charged values, as shown in Table 4-9. However, the EVA results confirmed that the LH2 tanker ship would be a promising and sustainable project in the future.

Table 4-9 Table 9 JAMILA ship economic value added (EAV)

Economic value-added estimation (Short term 2020)			
Year	2020	2021–2025	2025–2030
Capital invested (beginning of year) \$USD	600,665,360	119,847,200	119,847,200
Weighted average cost of capital (WACC) %	5	5.5	6
Finance charge \$USD	30,033,268	6,591,596	7,190,832
Net operating profit after tax \$USD	150,872,800	150,872,800	150,872,800
Economic value added \$USD	120,839,532	144,281,204	143,681,968
Economic value-added estimation (long-term 2040)			
Year	2040	2041–2045	2045–2050
Capital invested (beginning of year) \$USD	544,140,560	63,322,400	63,322,400
Weighted average cost of capital (WACC) %	5	5.5	6
Finance charge \$USD	27,207,028	3,482,732	3,799,344
Net operating profit after tax \$USD	216,997,600	216,997,600	216,997,600
Economic value added \$USD	189,790,572	213,514,868	213,198,256
Economic value-added estimation (long-term 2050)			
Year	2050	2051–2055	2055–2060
Capital invested (beginning of year) \$USD	544,140,560	63,322,400	63,322,400
Weighted average cost of capital (WACC) %	5	5.5	6
Finance charge \$USD	27,207,028	3,482,732	3,799,344
Net operating profit after tax \$USD	98,197,600	98,197,600	98,197,600
Economic value added \$USD	70,990,572	94,714,868	94,398,256

4.4 Conclusions

An established economic method was applied to assess the economic benefits for the LH2 tanker ship with a total capacity of 280,000 m³ as a future solution to contribute to achieving the global commitments to mitigate climate change. The economic feasibility was analysed using comprehensive economic models through three scenarios for the liquified hydrogen carrier ship. In the first scenario, short-term 2020, the hydrogen price was USD\$6/kg, and the hydrogen shipping price was USD\$1.2/kg. The second scenario, long-term 2040, assumes that the fuel price will decrease to USD\$2/kg, and the shipping cost will be the same as in the short-term 2020 scenario. Ultimately, the third scenario, long-term 2050, assumes that the hydrogen cost is USD\$2/kg and that the cargo shipping cost will decrease to USD\$0.7/kg from 2050. The results were found to be promising for the hydrogen economy. The key results are summarised as follows:

- The total capital cost of an LH2 tanker ship with 280,000 m³ of liquified hydrogen capacity was estimated to be approximately USD\$480,818,160; this represents an acceptable cost compared with the absolute total yearly income in each scenario.
- In the long-term 2050 scenario, the inflow value decreased by 58.3 % compared with the short-term 2020 and long-term 2040 scenarios due to the liquified hydrogen shipping cost decreasing from USD\$1.2 to USD\$0.7/kg. Therefore, the shipping cost plays a significant role in the total yearly income value of the LH2 tanker ship.
- In the long-term scenarios, the outflow value decreased by 50.2 % compared with that of the short-term 2020 scenario. This difference is due to the reduction in the liquified hydrogen price in the future, which caused a positive effect on the total yearly income value due to the decrease in fuel costs and the liquified hydrogen boil-off from the tanks.
- In the long-term 2040 scenario, the absolute 30-year income for 12 journeys/year achieved USD\$6,509,928,000, which was higher than those of the short-term 2020 and long-term 2050 scenarios. This difference was due to the hydrogen price reduction (i.e., USD\$2/kg, compared with USD\$6/kg in the short-term 2020 scenario) and the hydrogen shipping cost moderation (i.e., USD\$1.2/kg, compared with USD\$0.7/kg in the long-term 2050 scenario).

- In the long-term 2050 scenario, the NPV of USD\$1,698,036,169 was lower than that of the other scenarios; this NPV gain from the large-scale LH2 tanker ship project indicated that the investment is acceptable. The long-term 2040 scenario reached the highest NPV of USD\$3,752,329,725 with the same discount value of 4 %; this achievement is due to the high yearly income cash flow.
- In the long-term 2040 scenario, the IRR was 45.13 %, and in the worst-case scenario (i.e., the long-term 2050 scenario), the IRR was 20.25 %; these percentages can achieve a promising low-risk investment. This project's IRR achieved a very high and unusual percentage; this achievement is due to the very highly yearly income of the project compared with the project's total capital cost.
- The PP for the LH2 tanker ship investment in the short-term 2020, long-term 2040, and long-term 2050 scenarios require no more than 3.5, 2.5, and 6 years, respectively, to cover the project investment, which represents 11. 6%, 8.3 %, and 20 %, respectively, of the, assumed 30-year operational period of the LH2 tanker. These periods are profitable compared to other projects, and for the same reason as mentioned above, the yearly income of the project is very high compared to the total capital cost of the project.
- The EVAs for the short-term 2020, long-term 2040, and long-term 2050 scenarios were USD\$144,281,204.00, USD\$213,514,868.00, and USD\$94,714,868.00, respectively. The EVA results established that the LH2 tanker ship would be a promising and sustainable project in the future.

Credit Author Statement

Abdullah NFNR Alkhaledi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software. Suresh Sampath: Supervision. Pericles Pilidis: Supervision.

Declaration of Competing Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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5 PAPER 4 – TECHNO-ENVIRONMENTAL ASSESSMENT OF A HYDROGEN-FUELLED COMBINED-CYCLE GAS TURBINE FOR A LIQUID HYDROGEN TANKER

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Abstract

The purpose of this study was a techno-environmental assessment analysis for a 280,000 m³ liquid hydrogen (LH2) tanker powered by a hydrogen-fuelled combined-cycle gas turbine (COGAS) as the prime mover. This study utilised established and reliable methods to simulate the LH2 tanker in different journeys and conditions for analysing the advantages of the hydrogen-fuelled COGAS in terms of performance and emission reduction. The assessment was based on engine behaviour on different journeys under cargo load and no-load conditions, with a normal and a 6% degraded engine, and under various ambient conditions. According to the results, the single-pressure hydrogen-fuelled COGAS reached a maximum overall thermal efficiency of 55.5% in winter under no-load and normal engine conditions at a ship speed of 18 knots during the journey from Marseille to Algeria. From an environmental perspective, the maximum NO_x emission of the COGAS was 3.5 kg/h during the journey from Tangier to Southampton in summer with a 6% degraded engine under the load condition at a ship speed of 18 knots. The results of the techno-environmental assessment indicated that the LH2 tanker powered by the hydrogen-fuelled COGAS could successfully achieve high efficiency and low emission targets in off-design conditions. The outcome of this study will lead to a future investigation of the LH2 tankers operation economic aspects.

Keywords: Liquid hydrogen tanker; Engine thermal efficiency; Combined-cycle gas turbine; NO_x emissions; Hydrogen-fuelled engine; LH2 tanker mission

Abbreviations: COGAS: Combined-cycle gas turbine; LH2: Liquid hydrogen; IMO: International Maritime Organisation; 3D: Three-dimensional; NO_x: Nitrogen oxide; CO₂: Carbon Dioxide; CO: Carbon monoxide; SO_x: Sulphur oxide.

Units: **Tonnes:** Total displacement, Lightweight, Deadweight; **m:** LOA, Length between perpendiculars, Length on the waterline, Extreme breadth, Depth, Draught, Propeller diameter; **m²:** Wetted surface area; **knots:** Vessel speed; **MW:** Output power of combined-cycle gas and steam, Output power, Steam turbine output power, Pump work; **K:** Ambient temperature, Exhaust gas temperature, Turbine inlet temperature; **kPa:** Ambient pressure; **kg/kWh:** Specific fuel consumption; **kg/s:** Exhaust gas mass flow rate, Fuel flow rate, Steam mass flow rate; **%:** Thermal efficiency, Open-water efficiency; **°C:** Superheated steam temperature, Pinch point temperature difference, Approach point temperature difference, Feed water temperature; **bar:** Steam pressure, Condenser pressure; **rpm:** Propeller rotational speed; **g/kWh:** emission factor; **ppm:** concentration of gaseous species; **m³/h:** engine exhaust flow rate; **J/(mol K):** ideal gas constant; **kW:** engine power.

5.1 Introduction

Global sustainability requires urgent action to tackle climate change and global warming. Accordingly, world leaders at the UN climate change conference (COP26) in Glasgow took action to apply the 2015 Paris climate change agreement to overcome the negative impact of climate change and limit the global temperature increase to approximately 1.5 °C [1]. In the same direction, the International Maritime Organisation (IMO) aims to reduce 50% of greenhouse gas emissions from global shipping by 2050 compared to 2008 [2]. Regarding the environment, maritime transportation and shipping sectors are responsible for approximately 3% of the CO₂ emissions globally [3]. Moreover, several studies have shown that the continually growing CO₂, CO, and NO_x emissions from shipping are expected to play a crucial role in IMO regulations in future [4,5].

Additionally, the IMO applied the energy efficiency design index, a design instrument for reducing the emissions from newly constructed ships. The IMO also increased the strictness of the regulations on the NO_x and SO_x emissions from vessels and designated emission control areas, such as the Baltic and North seas [6]. In 2019, the United Kingdom was one of the countries that took action in this regard by publishing the UK Clean Maritime Plan to achieve zero-emission shipping by 2025. The plan indicated that the use of hydrogen fuel in vessel propulsion systems can play a significant role in the global transition to zero-emission shipping and transportation in the maritime sector [7].

Consequently, employing clean hydrogen can be a promising solution for global decarbonisation and climate change mitigation [8]. In actuality, the expectation indicates that hydrogen fuel has considerable potential to decarbonise the maritime sector if used in thermal engines by utilising the green hydrogen produced from renewable energy sources through electrolysis. Furthermore, hydrogen removes unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot, and smoke as harmful emissions [9]. The use of hydrogen as an energy storage mechanism is considered particularly useful in the context of electricity generated from sources where a significant mismatch between supply and demand is present; these include wind, solar, and nuclear sources, which could be used to electrolyse seawater rather than fresh water, which is scarce in many regions. Hydrogen can also be used with a thermal engine for waste heat recovery, such as a combined-cycle gas turbine (COGAS), to achieve higher thermal efficiency and lower emissions compared to those achieved using conventional internal combustion engines [9].

The combined cycle fuelled by hydrogen could be a successful alternative for ship propulsion systems to achieve almost zero-emission targets in the maritime sector. In this regard, the key issues are the ship design development and mission assessment in terms of the performance and environmental impact of a prime mover, such as liquid hydrogen (LH₂) tanker fuelled by hydrogen and powered by a COGAS as a prime mover [9].

However, interesting, exciting studies presented organic Rankine cycle, fuel cells, nuclear energy, batteries, superconducting motors, renewable energy, and hybrid propulsion as future marine propulsion technology with low fuel consumption and

emission reduction solutions [10]. Benvenuto et al. provided vital fundamental information for evaluating the performance of marine COGAS propulsion systems using a single- and dual-pressure heat recovery steam generator without using LH2 fuel [11,12]. Yan et al. studied the design optimisation of a cruise ship energy system using a multi-objective mathematical programming model that considered the technical, environmental, and economic aspects of ship function [13].

To the best of the authors' knowledge, the design and techno-environmental evaluation of hydrogen-fuelled COGASs for marine applications have not yet been investigated. This study makes a novel contribution by employing and examining a combined cycle gas turbine fuelled by hydrogen as an alternative efficient prime mover for a new design of hydrogen carrier ships in different journeys and ambient conditions to achieve an almost zero-emission target for the maritime transportation sector.

This study aimed to assess the missions of a novel upgraded hydrogen tanker powered by hydrogen-fuelled COGASs using the techno-environmental analysis method in off-design conditions in terms of the performance and environmental impact; for this purpose, the authors used state-of-the-art design and analysis methods.

5.2 Methods

An established methodology was developed to improve the novel design of the LH2 tanker with a total capacity of 280,000 m³ of LH2, which was designed in a previous study [8]. In addition, the methodology was analytically extended to assess the performance and emission for the upgraded design of the LH2 tanker using a techno-environmental assessment framework by applying a computational method for marine propulsion systems [14]. Developing the utilised method in this research could facilitate the design of a COGAS power plant fuelled by hydrogen as a prime mover to optimally reduce the fuel consumption and emissions of LH2 tankers. This upgraded design was performed using the in-house TURBOMATCH gas turbine performance code [15], MATLAB [16], and SOLIDWORKS software to design and simulate an LH2 tanker powered by a COGAS within POSEIDON, ship-wide in-house simulation software of Cranfield University. This approach evaluates proposed systems using the COGAS engine thermodynamic and environmental performance models. This study employed the hydrogen-fuelled COGAS as a prime mover to achieve the off-design requirements

from geographic location and ambient conditions for LH2 tankers in different journeys. In addition, the assessment considered the influence of the cargo weight, which was approximately 20,000 tonnes [8], and an engine degradation of 6% [9]. Further, the analysis provided a techno-environmental method for evaluating the ability of a proposed LH2 tanker to satisfy the zero-emission target with an efficient power system.

5.2.1 Overall Improved Design Philosophy

The overall design philosophy of the LH2 tanker has been presented in a previous study [8]. In the present study, only a few modifications were implemented to improve the previous design of the LH2 tanker; these modifications concerned adding new design elements represented by the LH2 tank pumps, ship anchors, storage facilities, and crew service tunnel. The updated design of the LH2 tanker is expected to improve applicability in the manufacturing sector.

5.2.2 Description of Techno-Environmental Modelling Modules

5.2.2.1 Ship Module

An upgraded design of the LH2 tanker named JAMILA was simulated in this study, as described in Section 5.2.1. The LH2 tanker evaluated in this research was 370 m long, 75 m wide, and had draughts of 9.263 and 10.012 m under the unloaded and fully loaded conditions, respectively. The full-load displacement was 230,000 tonnes for the transportation of 20,000 tonnes of LH2.

Moreover, the vessel used a single-pressure COGAS as the prime mover with an output power of approximately 50 MW [8]. The specifications of the LH2 tanker are listed in Table 5-1. To achieve adequate simulation accuracy, the authors assumed that the ship maintained a maximum operating speed of 18 knots during all journeys.

Table 5-1 Main characteristics of the simulated liquid hydrogen (LH2) tanker [8].

LH2 tanker parameters	Values	Units
Class	JAMILA	-
Vessel type	LH2 Tanker	-
Total displacement (Δ_{total})	230,000	tonnes
Lightweight	208,000	tonnes
Deadweight	22,000	tonnes
Length overall (LOA)	370	m
Length between perpendiculars	367.5	m
Length on the waterline	367.9	m

Extreme breadth (B)	75	m
Depth (D)	35	m
Full-load condition		
Draught (T)	10.012	m
Block coefficient (C_B)	0.819	-
Prismatic coefficient (C_p)	0.824	-
Midship coefficient (C_m)	0.995	-
Water plane coefficient (C_{wp})	0.900	-
Wetted surface area	29,551	m ²
No-load condition		
Draught (T)	9.263	m
Block coefficient (C_B)	0.813	-
Prismatic coefficient (C_p)	0.818	-
Midship coefficient (C_m)	0.994	-
Water plane coefficient (C_{wp})	0.894	-
Wetted surface area	28,916	m ²
Vessel speed	18	knots
Minimum propulsion power required for the full-load condition	27.3	MW
Output power of combined-cycle gas and steam	50	MW

5.2.2.2 COGAS and Propeller Module

The primary propulsion system of the ship was designed to be a 50-MW combined-cycle gas and steam turbine [9]. The performance of the power plant was analysed using an in-house gas turbine performance software [15] with hydrogen as an alternative fuel based on the gas turbine performance evaluation code [17]. The steam turbine was modelled and simulated using MATLAB software [16]. Additionally, the gas turbine cycle was inspired by an existing advanced LM2500+ gas turbine engine model, which is widely used in marine propulsion systems [18], and a single-pressure non-reheated steam cycle. The general specifications of the gas turbine and steam cycles are presented in Tables 5-2 and 5-3, respectively [9].

Consequently, in the design and off-design assessment, ambient temperature variations and a component degradation of 6% were considered. Moreover, two fixed-pitch propellers were assumed to be installed in the pods of the LH2 tanker. The vessel speed guided this selection and power requirement considering the size of JAMILA in accordance with the maximum allowable unloaded draught, which was 9.263 m, as mentioned in Table 5-1 [8]. The propeller design was based on the open-water characteristics of the Wageningen B-series propellers [19]. The main propeller design characteristics are listed in Table 5-4 [9].

Table 5-2 General specifications of a gas turbine cycle [9].

Gas turbine cycle	Values	Units
Ambient temperature	288.15	K
Ambient pressure	101.3	kPa
Pressure ratio	23.1	–
Specific fuel consumption	0.0742	kg/kWh
Exhaust gas mass flow rate	84.948	kg/s
Exhaust gas temperature	840.3	K
Turbine inlet temperature	1,550	K
Fuel flow	0.7485	kg/s
Output power	36.2	MW
Thermal efficiency	40.3	%

Table 5-3 General specifications of a steam cycle [9].

Steam plant parameters	Values	Units
Superheated steam temperature (T_a)	559.8	°C
Steam pressure (P_s)	60	bar
Pinch point temperature difference (ΔT_p)	7.5	°C
Approach point temperature difference (ΔT_a)	20	°C
Steam mass flow rate (m_s)	10.51	kg/s
Condenser pressure (P_{cond})	0.06	bar
Feed water temperature (T_e)	36.2	°C
Steam turbine output power (W_{ST})	14.35	MW
Steam turbine isentropic efficiency (η_{ST})	89.9	%
Pump work (W_{pump})	4.1388	MW

Table 5-4 Propeller design parameters and performance [9].

Propeller characteristic	Values	Units
Propeller type	Fixed pitch	–
Number of blades (Z)	4	–
Number of propellers	Twin-screw fixed on the pods	–
Propeller diameter (D_{pr})	6.4	m
Pitch ratio (P/D_{pr})	1.0	–
Blade area ratio (A_E/A_O)	0.9	–
Thickness-to-chord ratio (t/c)	0.029	–
Propeller rotational speed (n)	124.8	rpm
Open-water efficiency (η_o)	56	%

5.2.2.3 Vessel Resistance Prediction

The ship resistance model that affects the ship and power requirements in calm water has been comprehensively presented in a previous study on propulsion LH2 tankers [8]. The total resistance and power requirements of JAMILA were estimated using the Holtrop and Mennen method based on the ship shape and size [20,21]. In the present study, the authors considered the added wave and wind resistance in addition to the calm water resistance. These additional resistance modules, which are presented in the following sections, were expected to increase the accuracy of resistance estimation

under the load and no-load conditions for the LH2 tanker in different weather conditions.

5.2.2.3.1 Added Wave Resistance Module

The added resistance due to the wave motion resulting from the interaction of the vessel with normal waves was considered in this study, in contrast to the calm water resistance model presented in a previous study [8]. The combination of wave and ship motions produces a 20% to 40% increase in water resistance; this percentage cannot be neglected in the total resistance calculations [22]. According to Alexandersson [23], the added wave resistance can be estimated by considering the incident wave angles. This method is one of the most common procedures for accurately estimating the added resistance due to wave motion. The method of Gerritsma and Beukelman [24] is also used to estimate the added wave resistance. In this method, the linearised formulation is acceptable only for the head waves, for even keel vessels, especially when radiation-induced resistance is applied. The added wave resistance module used in the present study is based on a method described by Talluri et al. [25][26].

5.2.2.3.2 Wind Resistance Module

The method used here to estimate the aerodynamic resistance due to headwind was introduced by Jensen [27], expressed as follows:

$$R_{AA} = C_{AA} \frac{\rho_a}{2} \cdot (V + V_W)^2 \cdot A_{FP}, \quad 5-1$$

where R_{AA} is the wind resistance, C_{AA} is a coefficient in the range of 0.8–1.0 for cargo ships, ρ_a is the air density, V is the speed of the ship, V_W is the absolute value of wind speed, and A_{FP} is the frontal project area of the ship above sea level.

For all wind directions, the Blendermann model [28,29] was used by applying the following equation:

$$R_{AA} = \frac{\rho_a}{2} u^2 \cdot A_L \cdot CD_l \frac{\cos \varepsilon}{1 - \frac{\delta}{2} \left(1 - \frac{CD_l}{CD_t} \sin^2 2\varepsilon \right)}, \quad 5-2$$

where u is the apparent wind velocity; A_L is the lateral plane area; ε is the apparent wind angle, which is zero in the case of headwind; δ is the cross-force parameter; CD_l is the non-dimensional drag under the headwind condition; and CD_t is the non-dimensional drag under the beam wind condition.

5.2.2.3.3 Engine Performance

The engine performance model ENGINE was one of the main modules in the numerical software POSEIDON, which was used to implement the combined-cycle model and LH2 tanker design for simulating the performance of the LH2 tanker powered by the hydrogen-fuelled COGAS in different journeys and conditions [14]. ENGINE estimated the engine performance using a three-dimensional (3D) interpolation function that obtained the engine power at each operating point. The input values were obtained by changing the turbine inlet temperature and ambient conditions through the combined-cycle performance and stored as a three-dimensional table [25]. In this study, ENGINE was used to simulate the COGAS model with the turbine inlet temperature ranging from 1025 to 1700 K in increments of 25 K and the ambient temperature ranging from -25 to 45 °C in increments of 10 °C; these values were selected to cover a large scale of the turbine inlet temperature variation in the winter, summer, and middle seasons.

5.2.2.4 Weather and Journey Management Module

In practice, the weather module input variables are the ambient temperatures of air and sea between the hydrogen exporting and importing ports [14]. In this study, the operation period of the LH2 tanker was assumed to be 330 days per year; this period was divided into three seasons (winter, summer, and middle) to achieve the actual evaluation results of the ship performance and emission. The winter months were December, January, and February; summer months were June, July, and August; and middle-season months were March, April, May, September, October, and November. The average ambient temperature of each season was applied in the LH2 tanker simulation for different journeys. The journey management model includes the trip distance, ship speed, and time periods with changing weather conditions and estimates the total trip time and the total fuel consumption of the engine [14]. This study selected the trips based on the expectation of the hydrogen exporting hubs, which are sunny countries with ports. Therefore, two journeys were selected: from Marseille to Algeria (22 h) and from Tangier to Southampton (81 h). Each season, the journeys were simulated to realise adequate accuracy in the engine performance and emission analysis. In this stage of hydrogen storage technologies, the journeys are assumed to be short (not more than 4 d), owing to the relatively high boil-off rate.

5.2.2.5 Emission Module

The LH2 tanker in this study was assumed to be transporting and fuelled by zero-carbon green hydrogen, producing only low NO_x gaseous emissions [30]. From an environmental perspective, the model for assessing the NO_x output emissions from a loaded and unloaded green LH2 tanker powered by the hydrogen-fuelled COGAS in different off-design operation conditions and journeys was predicted using emission factor estimation. The emission factor of the 50-MW hydrogen-fuelled COGAS as a prime mover can be calculated using Eq. (5-3) [31]:

$$EF_{i,k} = (E_{i,k} \times 10^{-6}) \left(\frac{P.V}{R.T} \times \frac{MW_k}{P_p} \right), \quad 5-3$$

where $EF_{i,k}$ is the emission factor (g/kWh); i refers to the engine type; k refers to the emission type; E is the concentration of gaseous species (ppm); P is the pressure (N/m²); V is the engine exhaust flow rate (m³/h); R is the ideal gas constant, which equals 8.3145 J/(mol K); T is the exhaust gas temperature (K); MW is the molecular weight; and P_p is the engine power (kW). The LM2500+ gas turbine, which was used in this study, was not designed to be exclusively fuelled by hydrogen, and there is much scope for future research in this field. Therefore, the authors adopted the maximum value of the concentration of gaseous species for this type of gas turbine, which is 25 ppm [32]. Consequently, the NO_x emission for each journey hour using fuel flow can be calculated by Eq. (5-4) [33]:

$$E_{NOx} = F.F. \times EF_{i,k}, \quad 5-4$$

where E_{NOx} is the NO_x emission and $F.F.$ is the gas turbine fuel flow per hour during the journey. The LH2 tanker was simulated for three seasons (winter, summer, and middle) using COGAS NO_x emission estimation considering the ship operation hours during two journeys (from Marseille to Algeria and from Tangier to Southampton). The simulation of ship NO_x emission was studied under the impact of a normal and a 6% degraded engine under load and no-load conditions.

5.3 Results and Discussion

The performance and emission results for the improved design of JAMILA are presented in this section. In this study, a techno-environmental assessment based on engine behaviour for different journeys under load and no-load conditions, a normal and

a 6% degraded engine, and varying ambient conditions were conducted to assess the prime mover as an environmentally friendly propulsion system.

5.3.1 Results of design assessment

Figure 5-1 shows the design of the improved LH2 tanker after adding new design elements, such as hydrogen tank pumps, ship anchors, storage facilities, and the crew service tunnel [8]. The improved design that includes a hydrogen-fuelled COGAS as the prime mover without any additional propulsion technologies can be used in future applications.

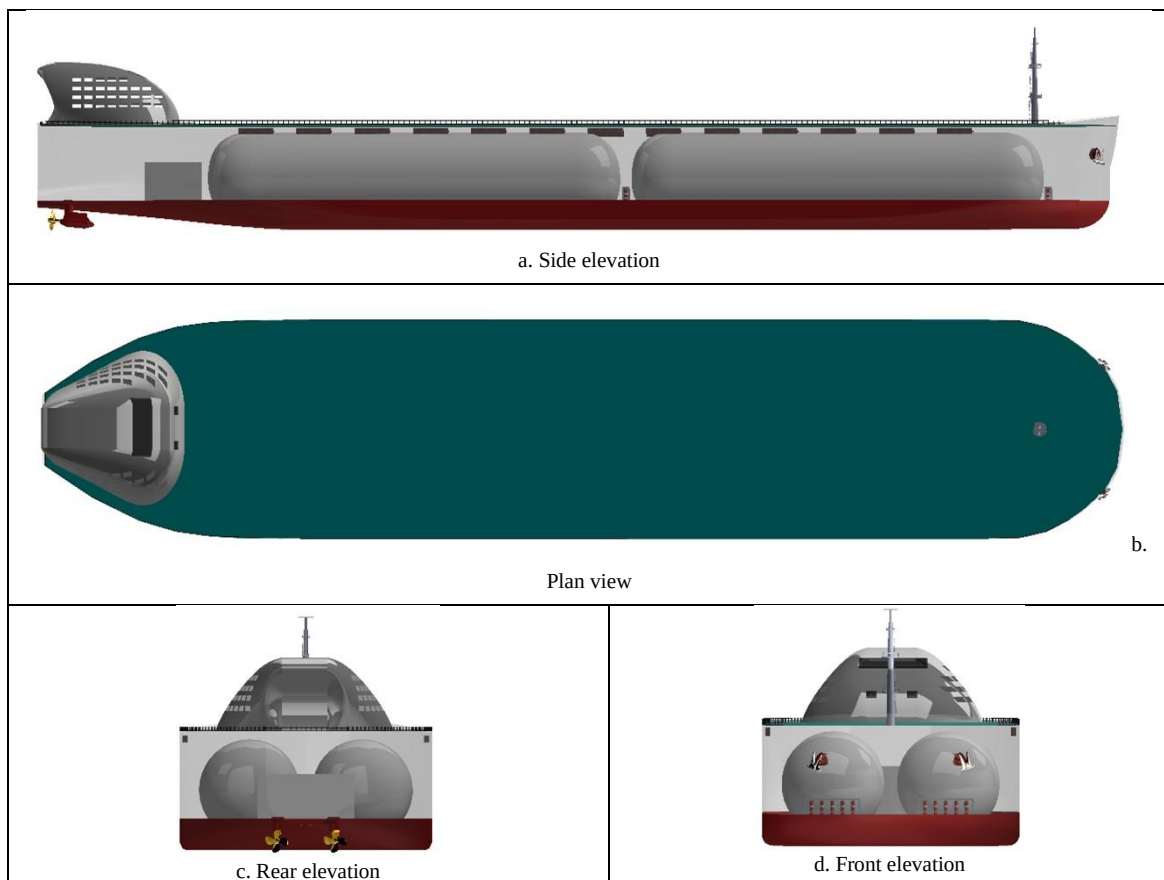


Figure 5-1 JAMILA three-dimensional design; (a) side elevation; (b) plan view; (c) rear elevation; and (d) front elevation.

5.3.1.1 Results of Weather and Journey Routes

In this study, the weather estimation showed a variety of ambient temperatures between different journeys for the winter, summer, and middle seasons. For this reason, two journeys were analysed in terms of the ambient conditions. The Marseille–Algeria

journey showed that the maximum temperature in summer was more than 30 °C, compared to 25 °C for the Tangier–Southampton journey. The increase in the ambient temperature may negatively influence the ship engine performance and emissions. The middle season assumed in this study represented approximately six months of the year, and the maximum temperature during the Marseille–Algeria journey in this season was approximately 22 °C, compared to 24 °C for the Tangier–Southampton journey. In winter, the maximum temperature during the Marseille–Algeria journey was less than 15 °C, compared to 21 °C for the Tangier–Southampton journey. Figure 5-2 shows the weather conditions in the winter, summer, and middle seasons during the Marseille–Algeria and Tangier–Southampton journeys.

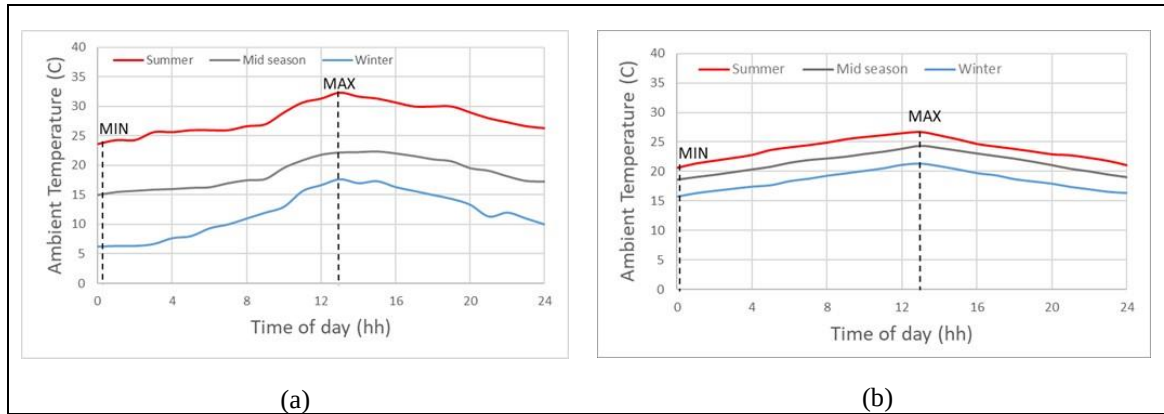


Figure 5-2 Weather conditions in different seasons during the (a) Marseille–Algeria and (b) Tangier–Southampton journeys. Credits: timeanddate.com.

5.3.1.2 Ship Performance Analysis

Two journeys were selected to assess the performance of the COGAS as a prime mover. The ship off-design performance was analysed in terms of the overall thermal efficiency of the COGAS as a prime mover. The prime mover performance was simulated under the no-load condition and a load of 20,000 tonnes of LH2 for a one-way journey in each case. In addition, the performance of the ship engine was assessed under different weather conditions to investigate the single-pressure COGAS behaviour. Figure 5-3 shows the overall thermal efficiency of the hydrogen-fuelled COGAS during the one-way Marseille–Algeria journey for three seasons (winter, summer, and middle). The result shows that the COGAS as a prime mover could achieve the required power with a ship speed of 18 knots in all conditions except in summer with a degraded engine; in

summer, the vessel speed required reducing to 17 knots because the required ship power was more than the COGAS power output due to the high ambient temperature and the influence of 6% degradation. The results showed that the overall thermal efficiency of the normal COGAS under the no-load condition in winter could reach 55.5%, representing the maximum overall thermal efficiency of all conditions. The minimum overall thermal efficiency was 49.7%, which occurred in summer under the load condition with a 6% degraded engine.

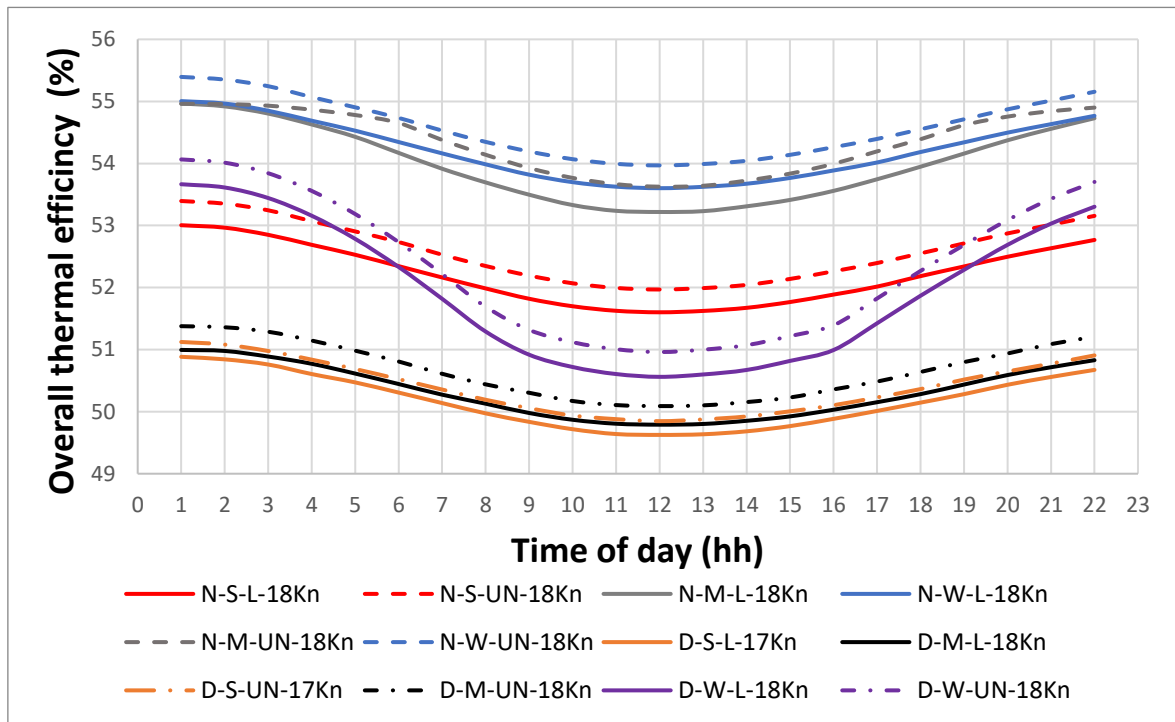


Figure 5-3 Overall thermal efficiency of the LH2 tanker with a combined-cycle gas turbine (COGAS) as a function of journey time under different conditions for the Marseille–Algeria journey. N: normal engine, D: degraded engine, W: winter, S: summer, M: middle season, L: load condition, and UN: no-load condition.

Similarly, the Tangier–Southampton journey was simulated for three seasons under different conditions, as shown in Figure. 5-4. The results showed that the maximum overall thermal efficiency of the normal COGAS under the no-load condition was 55%. The minimum overall thermal efficiency was 49.2%, which occurred under the full-load condition with a 6% degraded engine.

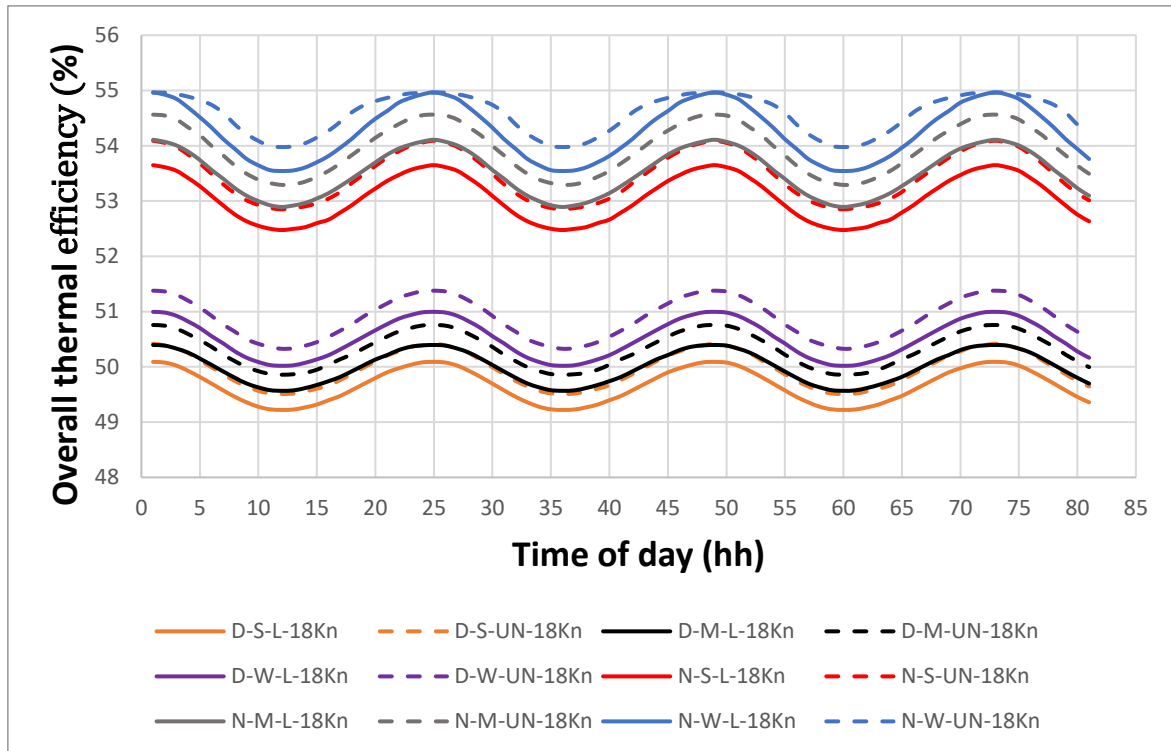


Figure 5-4 Overall thermal efficiency of the LH2 tanker with a COGAS as a function of journey time under different conditions for the Tangier–Southampton journey.

The difference of the maximum and minimum overall thermal efficiencies of the LH2 tanker propulsion system between the Marseille–Algeria and Tangier–Southampton journeys was approximately 0.5%. This difference resulted from the ambient temperature variation between the different seasons. In particular, during the Marseille–Algeria journey in summer, the maximum ambient temperature was higher than 30 °C, while the corresponding maximum for the Tangier–Southampton journey was 27 °C, as shown in Figure 5-2. Hence, the minimum overall thermal efficiency of the ship engine in the Marseille–Algeria journey should be lower than that in the Tangier–Southampton journey; however, the results showed were the opposite. This happened because the vessel speed decreased from 18 to 17 knots, increasing the minimum overall thermal efficiency of the LH2 tanker engine in the Marseille to Algeria journey.

5.3.1.3 Environmental assessment results

This section describes the emission analysis of the LH2 tanker propelled by the COGAS during two different journeys (Marseille–Algeria and Tangier–Southampton). The LH2

tanker was simulated for three seasons (winter, summer, and middle) in terms of the COGAS NO_x emissions with respect to the ship operation hours for each journey. The ship NO_x emissions were examined in the case of a normal and a 6% degraded engine under the load and no-load conditions. Because the fuel consumed in the COGAS engine is zero-carbon green hydrogen, which produces NO_x emissions, only NO_x emissions were considered in this study. Figure 5-5 shows the NO_x emissions from the LH2 tanker propelled by the hydrogen-fuelled COGAS during the one-way Marseille–Algeria journey, which lasted for 22 h, under different ambient conditions. The maximum amount of NO_x emissions from the LH2 tanker engine was 3.5 kg/h in the case of a degraded COGAS in the middle season at a ship speed of 18 knots. The minimum amount of NO_x emissions was 2.6 kg/h in the case of a degraded COGAS in summer at a ship speed of 17 knots. However, the results clarify that the NO_x emissions may decrease with decreasing ship speed regardless of the season and engine condition.

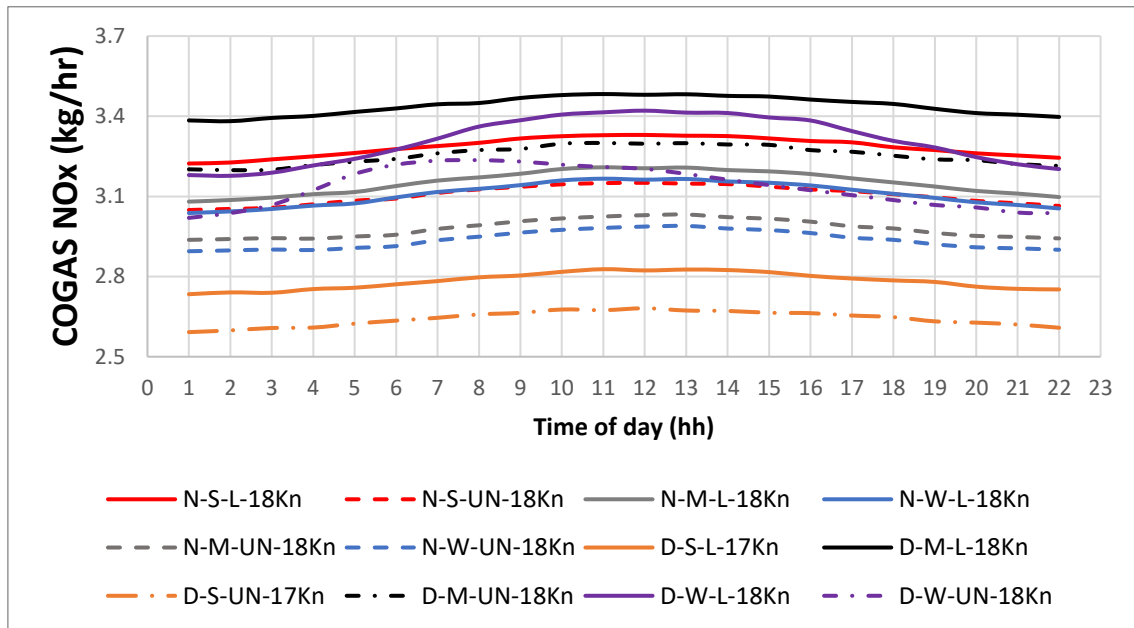


Figure 5-5 NO_x emissions from the LH2 tanker with a COGAS as a function of journey time under different conditions for the Marseille–Algeria journey.

Figure 5-6 presents the estimation of the NO_x emissions during the one-way Tangier–Southampton journey, which lasted for 81 h, under different ambient conditions for three seasons. The results show that the maximum amount of NO_x emissions was 3.6 kg/h in the case of a degraded COGAS under the full-load condition in summer at a ship speed of 18 knots. The minimum amount of NO_x emissions was 2.95 kg/h at a ship

speed of 18 knots. In the case of a constant ship speed of 18 knots, the journey season and cargo weight played a key role in controlling the NO_x emissions from the LH2 tankers.

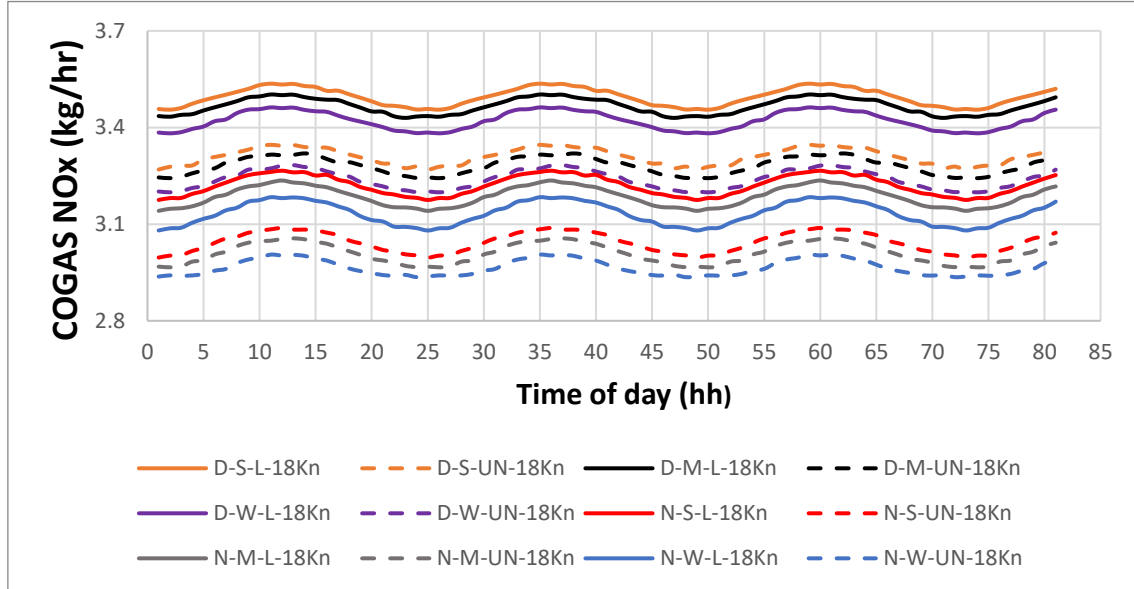


Figure 5-6 NO_x emissions from the LH2 tanker with a COGAS as a function of journey time under different conditions for the Tangier–Southampton journey.

Between the Marseille–Algeria and Tangier–Southampton journeys, the maximum amount of NO_x emissions from the LH2 tanker did not vary. The reason for these unusual results is that the maximum amount of NO_x emissions in the Marseille–Algeria journey was generated in the middle season, whereas that in the Tangier–Southampton journey was produced in summer. The minimum amount of NO_x emissions in the Tangier–Southampton journey was approximately 10% higher than that in the Marseille–Algeria journey. The increased NO_x emissions resulted from the increased speed of the LH2 tanker from 17 to 18 knots.

5.4 Conclusions

An established techno-environmental assessment method was applied to a 280,000 m³ LH2 tanker propulsion system with a hydrogen-fuelled COGAS as the prime mover. The performance and emissions were analysed based on the engine behaviour for different journeys under load and no-load conditions, a normal and a 6% degraded engine, and varying ambient conditions for the LH2 tanker prime mover. The results

were promising in terms of the propulsion system performance and environmental benefits; the key results can be summarised as follows.

- An LH2 tanker design was improved to enhance its applicability by adding new design elements, such as hydrogen tank pumps, ship anchors, storage facilities, and a crew service tunnel.
- Two international journeys were investigated in terms of ambient temperatures and normal/degraded engine conditions for a realistic simulation environment. The hydrogen tanker powered by a COGAS was simulated for three seasons (winter, summer, and middle) for the Marseille–Algeria and Tangier–Southampton journeys. The COGAS achieved the required power at a ship speed of 18 knots in all conditions except in the Marseille–Algeria journey in summer with a degraded engine; in summer, the vessel speed required to be reduced to 17 knots because the required ship power was more than the COGAS power output due to the high ambient temperature and the influence of 6% degradation. The ambient temperature and engine condition played a crucial role in influencing the ship speed.
- The assessment results for the LH2 tanker propulsion system performance indicated that the hydrogen-fuelled COGAS could achieve a maximum overall thermal efficiency of 55.5% in the Marseille–Algeria journey in winter with a normal engine under no-load conditions; the corresponding maximum for the Tangier–Southampton journey was 55%. The variation in the overall thermal efficiencies depended on ambient temperature, cargo weight, and engine condition.
- Regarding the environmental impact, the maximum amount of NO_x emissions from the 50-MW hydrogen-fuelled COGAS was 3.6 kg/h in the Marseille–Algeria journey with a degraded engine in the middle season at a ship speed of 18 knots. The minimum amount of NO_x emissions was 2.6 kg/h for the same journey in the case of a degraded COGAS in summer at a ship speed of 17 knots. Moreover, the minimum amount of NO_x emissions during the Marseille–Algeria journey was 10% lower than that in the Tangier–Southampton journey. The decreased

NO_x emissions resulted from the decreased speed of the LH₂ tanker from 18 to 17 knots in the Marseille–Algeria journey. Hence, the amount of NO_x emission was substantially influenced by the ship speed.

To conclude, the assessment results signify that the employment of the hydrogen-fuelled COGAS for a large-scale LH₂ tanker has significant benefits, compared to the conventional propulsion systems, in terms of achieving the required overall thermal efficiency and reducing the NO_x emissions of the prime mover.

Declaration of Competing Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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6 PAPER 5 – TECHNO ENVIRONMENTAL ASSESSMENT OF FLETTNER ROTOR AS ASSISTANCE PROPULSION SYSTEM FOR LH₂ TANKER SHIP FUELLED BY HYDROGEN

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Abstract

This study presents a novel design and development of a 280,000 m³ liquefied hydrogen tanker ship by implementing a set of 6 Flettner rotors as an assistance propulsion system in conjunction with a combined-cycle gas turbine fuelled by hydrogen as a prime mover. The study includes assessment of the technical and environmental aspects of the developed design. Furthermore, an established method was applied to simulate the LH₂ tanker in different voyages and conditions to investigate the benefits of harnessing wind energy to assist combined-cycle gas turbine in terms of performance and emission reduction based on engine behaviour for different voyages under loaded and unloaded, normal as well as 6% degraded engine, and varying ambient conditions. The results indicate that implementing a set of 6 Flettner rotors for the LH₂ tanker ship has the potential to positively impact the performance and lead to environmental benefits. A maximum contribution power of around 1.8 MW was achieved in the winter season owing to high wind speed and favourable wind direction. This power could save approximately 3.6% of the combined-cycle gas turbine total output power (50 MW) and cause a 3.5% reduction in NO_x emissions.

KEYWORDS: Liquefied hydrogen; LH₂ tanker mission; Renewable energy; LH₂ tanker Performance; Flettner rotors; Environmental

6.1 Introduction

Limiting the overall global temperature rise to 1.5 °C to save the global environment, as agreed by a majority of member nations at the 2021 UN Climate Change Conference held in Glasgow, represents a significant challenge [1]. In April 2018, The International Maritime Organization (IMO), London, adopted the initial GHG strategy that included, among others, reducing GHG emissions from international shipping by at least 50%, in comparison to emissions in 2008, by 2050. Additionally, the initial GHG strategy set a target to reduce CO₂ emissions from shipping by at least 40% by 2030 and 70% by 2050, in comparison to emissions in 2008 [2]. Furthermore, the United Kingdom published the Clean Maritime Plan in July 2019 as an environmental route map to achieve the UK vision of maritime 2050. The government published it to transition to a future zero-emission shipping in UK waters with the expectation that by 2025 all-new vessels in UK waters will be designed with zero-emission propulsion capability. The plan suggested that hydrogen fuel and renewable energy for vessel propulsion systems could be substantial and applicable solutions in the global transition to zero-emission shipping and transportation in the maritime sector [3].

Renewable energy technologies are attractive options to achieve the zero-emission target in the marine sector. Hence, there is a global effort to develop the use of sustainable renewable energy as a ship's propulsion technology. However, renewable energy is an old concept and modern technology; in the past 150 years, there has been a significant transformation in the propulsion energy sources of ships, such as switching from the sail (renewable energy) to using coal, heavy fuel oil (HFO) and marine diesel oil (MDO).

Consequently, utilising clean hydrogen and renewable energy can be promising solutions for global decarbonisation and achieving climate change targets [4, 5]. Furthermore, applying renewable energy technologies as a complementary propulsion system for ships could be an effective solution to overcome the negative impact of fossil fuel consumption and emissions [6]. Wind-assisted propulsion obtained through the application of Flettner rotor technology has significant potential as a ship assistance propulsion system to the ship's prime mover in saving fuel consumption, increasing thermal efficiency, and decreasing emissions [5]. Therefore, a hydrogen-fuelled

combined cycle power plant in conjunction with Flettner rotor technology as a new concept could be a successful alternative ship propulsion system to reach the maritime sector's high-efficiency and low-emission targets. To achieve maritime emission reduction targets, there is a need for the development of alternative ship propulsion system designs and assess them in terms of the performance and environmental impact. Such as the design and development of a clean ship prime mover such as a liquefied hydrogen tanker ship fuelled by hydrogen and powered by a combined cycle gas turbine as the ship prime mover in conjunction with a sustainable renewable energy powered propulsion system as an assistant to the prime mover could help ensure sustainability and achievement of maritime emission reduction targets [7, 5].

Previously completed research works have focused on designing and evaluating Flettner rotors as an assistance marine propulsion system. Talluri et al. [5] applied a Techno-economic, Environmental and Risk Assessment (TERA) methodology to assess the performance and economic benefits of utilising a 4.5 MW simple cycle, twin-shaft marine gas turbine fuelled by natural gas and twin-diesel engines, each of 3 MW rating, operating on marine diesel oil as ship power plants in conjunction with three Flettner towers. The results show that installing three Flettner towers on commercial vessels could save 20% in terms of fuel consumption and a similar percentage in emission reduction. Additionally, Traut et al., [8] assessed the potential for harnessing wind power for shipping using a Flettner tower and towing kite technology in five trade routes. The results show that the average savings attained by applying the propulsive power contribution of the kite technology is lower when compared to the propulsive power contribution of single Flettner rotor technology [8]. Zhang P. et al. [9] investigated the environmental and economic advantages of the Flettner rotor and parafoil systems based on the TERA framework. Bordogna et al. [10] discussed the aerodynamic performance and efficiency of Flettner rotors while mainly focusing on the fuel-saving potential during ship operation. To the best of the authors' knowledge, the design and techno-environmental evaluation of hydrogen-fuelled combined-cycle gas turbines in conjunction with Flettner rotor technology for marine applications has not been considered yet.

This study aims to design and assess the performance and environmental impacts of a novel hydrogen-tanker ship powered by hydrogen-fuelled combined-cycle gas turbines in off-design conditions in conjunction with 6 Flettner rotors, using the techno-environmental analysis method.

6.1.1 Flettner Rotors

The Flettner rotor is a pioneering technology invented by Anton Flettner in the 1920s to serve as an alternative marine propulsion technology to the traditional sails that were in use for shipping at that time [11]. Historically, Flettner rotors were utilised and examined as a propulsion system for ships, but the technology was deserted after the manufacture of steam and diesel engines became widespread. However, as a consequence of the shipping crisis of the 1980s, the shipping sector reconsidered utilising Flettner rotors [12]. Recently, the shipping sector has been focused again on developing and utilising this technology as an alternative propulsion solution to achieve the maritime zero-emission target. In 2010, the Flettner rotor was further developed by ENERCON, which launched the E-SHIP1 as its first trial ship [13]. Lately, the Flettner rotors have been classified as a promising alternative maritime shipping propulsion system owing to their ability to significantly lower fuel consumption and the corresponding emission reduction [14]. The physical principle of the Flettner rotor is that rotations induce the Magnus effect to produce thrust perpendicular to the wind direction. The generated force is linearly related to the wind speed and direction, resulting in an affirmative forward thrust at the various ship wind speeds [15]. Several studies considered the Flettner rotor's general characteristics and aerodynamic performance using computational fluid dynamics (CFD) [16, 17]. Lu R. et al. [18] compared three wind-assisted ship propulsion technologies, viz. the Flettner rotor, a wind sail, and the DynaRig concept, in the Aframax Oil Tanker in the route between Gabon and Canada. This study revealed that the ship type, speed, voyage routes, and weather conditions significantly influence the extent of fuel savings possible. Moreover, the results showed that the Flettner rotor achieved the most significant fuel-saving percentage in comparison with the other technologies [18]. In 2015, a 9700 DWT Ro-Ro Carrier achieved an annual 5% fuel saving after installing two Norsepower rotors with a dimension of 18 m in height and 3 m in diameter (www.norsepower.com). This

research study examines the ability of the Flettner rotors to assist the ship prime mover to increase the engine's thermal efficiency, thereby reducing fuel consumption and maritime emission in different voyages as well as conditions.

6.2 Methodologies

In 2021, an authentic method was established by Alkhaledi A.N. et al. [4] to design a 370 m long, 75 m wide LH2 tanker ship with a total capacity of 280,000 m³ of liquefied hydrogen. In this study, a set of 6 Flettner rotors to be installed on the deck of the designed ship as a clean assistance propulsion system. An analytically expanded methodology was applied to evaluate the performance and emission of the suggested designs of the LH2 tanker ship using a techno-environmental assessment framework by employing a TERA computational method developed for marine propulsion systems [19]. In this study, a COGAS power plant fuelled by hydrogen in conjunction with 6 Flettner rotors was developed as a novel integrated propulsion system for an LH2 tanker ship design. The method developed in this study will assist the implementation of the design of a COGAS power plant fuelled by Hydrogen as the prime mover system and assisted by sustainable renewable energy technology to increase the prime mover thermal efficiency and reduce the engine emissions for LH2 carrier vessels. Several numerical design models and simulation tools were employed to integrate the Flettner towers with the LH2 tanker ship hull and assess this design in terms of LH2 tanker ship engine performance and emissions. In terms of design, SOLIDWORKS software was used to integrate all the 6 Flettner towers with the LH2 tanker ship hull. Moreover, the COGAS power plant fuelled by hydrogen as the prime mover was designed and examined using in-house "TURBOMATCH gas turbine performance code" [20] and MATLAB software [21]. After the design of the LH2 tanker ship integrated with a set of 6 Flettner rotors and the COGAS engine examination, the inclusive ship design was simulated. The purpose of the simulation was to investigate the Flettner towers' harnessing into the prime mover of the LH2 tanker ship in terms of COGAS fuelled by hydrogen performance and emissions in different ambient conditions and voyages using in-house "Poseidon" Cranfield university simulation software.

In addition, the evaluation of the ship's performance and emissions analysis takes into account the influence of the cargo weight, which is estimated as 20,000 tonnes [4], and

degradation of 6% in the case of COGAS fuelled power plant as a ship prime mover [22]. Furthermore, the assessment offered a techno-environmental evaluation method to be an applicable method for evaluating the capability of the suggested LH2 tanker ship to meet the emission reduction target with a highly effective integrated ship propulsion system.

6.2.1 Design Philosophy

The renewable energy enhancement model is designed using a Flettner rotor model, considering the technology size, weight, and distance between towers based on the LH2 tanker ship size. A set of 6 Flettner rotors was installed as an assistance propulsion system on the deck of the LH2 tanker ship, which was designed and assessed by [4, 7]. The Flettner towers were designed as an assistance propulsion system for the COGAS power plant prime mover of the LH2 tanker ship fuelled by hydrogen. Each Flettner rotor is 8 m in diameter, 40 m in height, and equipped with a 12 m rotor disc; the dimensions were chosen based on the ship size and deck area. Technically, the design spacing distance between each Flettner tower is equal to one tower height, which is 40 m. This distance ensures avoidance of aerodynamic interference between each other [5]. Moreover, the ship's overall length is only 370 m, which is a serious limitation of the deck area, and there is no room to install additional Flettner towers. Additional design details are provided in the following sections.

6.2.2 Techno-Environmental Modelling Modules

6.2.2.1 Vessel Module

A new design of LH2 carrier vessels was designed and simulated in this study. The modern JAMILA ship design includes a COGAS power plant as the ship prime mover and a set of 6 Flettner rotors as an assistance propulsion system. This research study is an assessment of a LH2 tanker ship that is 370 m long, 75 m wide, and has a draft of 9.263 m and 10.012 m under unloaded and fully loaded conditions, respectively. The fully loaded displacement tonnage is 230,000 tonnes of liquefied hydrogen.

In addition, 6 Flettner rotors with dimensions of 40 m height and 8 m diameter were installed on the ship deck to function as an assistance propulsion system to the ship's prime mover, which is a 50 MW single pressure combined-cycle gas turbine, to achieve

the fuel-saving and emission reduction targets. The main characteristics of the LH2 tanker ship have been described in detail in reference [4]. However, from the ship's stability point of view, considering the lightweight of the Flettner rotors in comparison to the LH2 tanker's overall size and weight, the installation of the 6 Flettner towers is not expected to influence the ship's stability performance or maximum allowable vessel displacement [4]. To reach the simulation accuracy target for the LH2 tanker in this research, the authors have assumed that the ship maintains a maximum operating speed of 18 knots during all voyages and follows linear and direct routes with no weather related or physical geographical obstructions during the different simulated voyages.

6.2.2.2 Prime Mover and Flettner Rotor Module

The LH2 tanker ship simulated in this study, which has been named as JAMILA ship, is equipped with a prime mover of 50 MW single pressure non-reheat combined-cycle gas turbine fuelled by hydrogen to achieve the high efficiency and low emission targets; this prime mover and propeller module are described in detail in reference [7]. Furthermore, six Flettner rotors were designed, simulated, and located based on the size of the upgraded design of the liquefied hydrogen ship. The Flettner rotors with 40 m height, 8 m diameter, 6.3 spin ratio, and 12 m diameter rotor disc function as an assistance propulsion system with COGAS to achieve the optimum output power from the wind energy technology and increase the propulsion system thermal efficiency by decreasing the prime mover fuel consumption and emissions. Table 6-1 lists the main characteristics of the Flettner rotors. Two forces are generated by the Flettner rotor on board the vessel: the lift force (L) working vertically to the local apparent wind direction and the drag force (D) working in the same direction as the local wind direction. Those forces are expressed using force coefficients which can be estimated using the equations (6-1), (6-2), (6-3), and (6-4) [23, 15, 5]. In this study, the lift and drag coefficients related to spin ratio 6.3 equal 12.8 and 4.3, respectively.

$$L = \frac{1}{2} \rho_a A v_a^2 C_L \quad 6-1$$

$$D = \frac{1}{2} \rho_a A v_a^2 C_D \quad 6-2$$

$$C_L = -0.0046 SR^5 + 0.1145 SR^4 - 0.9817 SR^3 + 3.1309 SR^2 - 0.1039 SR \quad 6-3$$

$$C_D = -0.0017 SR^5 + 0.0464 SR^4 - 0.4424 SR^3 + 1.7243 SR^2 - 1.641 SR + 0.6375 \quad 6-4$$

where ρ_a is the density in kg/m^3 , A is a Flettner rotor area in m^2 , v_a is apparent wind velocity in m/s , C_L and, C_D are lift and drag coefficients, respectively, and SR is the spin ratio.

Each Flettner rotor needed electric power to rotate around its axis; this power can be estimated using the method explained in reference [23]. The consumed power must be considered in the Flettner rotors performance prediction. This power (p_{req}) can be estimated using equations (6-5) and (6-6), where C_p is the power coefficient.

$$C_p = \frac{p_{req}}{0.5\rho_a A v_a^3} \quad 6-5$$

$$C_p = 0.0001 SR^5 - 0.0004 SR^4 + 0.0143 SR^3 - 0.0168 SR^2 + 0.0234 SR \quad 6-6$$

Table 6-1 Flettner rotor characteristics

Tower features	value	units
Aspect ratio value	5	-
Endplates to cylinder diameter ratio	1.5	-
Spin ratio	6.3	-
Flettner rotor diameter	8	m
Flettner tower height	40	m
Number of Flettner towers	6	-
Distance between each Flettner tower	40	m
Maximum power required to rotate all the towers	0.3	MW
Maximum total output power from all the towers	1.8	MW
Fuel saving percentage achievement	3.6	%
Flettner rotor disc diameter	12	m

Design of the Flettner rotors was undertaken based on the characteristics presented in Table 6-1; the LH2 tanker engine performance was estimated assuming the installation of 6 rotors on the ship deck. The space between the installed rotors play a key role in the performance of the Flettner rotors because of the aerodynamic interference between each other, which could directly affect the towers' performance. Consequently, based on the size of the ship deck, 40 m spacing, which is equal to the height of one tower, was determined to be the appropriate space between each other on the ship deck to avoid any aerodynamic interference. However, certain assumptions were made to simulate the actual operating conditions under the vessel's new design. First, it was assumed that each tower could achieve its maximum power capability under all weather conditions except during headwind conditions. Second, when the resultant forces generated by the rotors are directed against the ship's direction of motion, all the towers are assumed to be out of service and function as additional wind resistance surfaces.

6.2.2.3 Ship Resistance and Engine Performance Estimation

The LH2 tanker ship resistance model that influences the ship and power requirements in calm water is described in detail in a previous study for propulsion of liquefied hydrogen fuelled LH2 carrier design [4]. The vessel shape and dimensions of the JAMILA ship lead to the estimation of the total resistance model and power requirements using the Holtrop and Mennen method [24, 25]. In this study, the authors have considered the added wave and wind resistance models in addition to the total calm water resistance to increase the accuracy of resistance estimates in loaded and unloaded conditions for the liquefied hydrogen tanker ship in different weather conditions and voyages. More details on these additional resistance modules are presented in previous studies [7, 5]. The engine performance model embodied as a leading model in a numerical "Poseidon" software to simulate the performance of LH2 carrier ship powered by COGAS hydrogen-fuelled in conjunction with the Flettner rotors technology in different voyages and conditions is presented in reference [19]. The engine performance module is described in detail by reference [22].

6.2.2.4 Weather and Voyages Conditions Module

The ambient temperature of air and sea, sea state, and wind speed between the hydrogen exporting and importing ports are considered the most important input variable in the weather model [19]. For this research, 330 days per year were assumed under three seasons (summer, winter, and autumn) as an operational period of the LH2 tanker ship to achieve authentic assessment results of the ship performance and emission. The following two voyage routes were selected for the study, viz., Marseille to Algeria (22 hours sailing time) and Tangier to Southampton (81 hours sailing time). The ports that were expected to transform as future hydrogen hubs and the countries that benefit from extensive sunshine with a coastline were the criteria used to select the voyage routes. The voyages were simulated for all three seasons to achieve authenticity in the engine performance and emission analysis. Considering the existing hydrogen storage technologies in vogue as well as the relatively high boil-off percentage, short voyages not exceeding four days have been considered for the study. Additional details of the voyage management model are described in reference [19].

6.2.2.4.1 Wind Routine Estimation

The authors used the Climatology of Global Ocean Winds (COGOW) database and the data collected from Oregon State University's Cooperative Institute for Oceanographic Satellite Studies [26, 5] to extract the wind speed and direction data. The data selection was made based on determining the voyage's itinerary and taking the average wind velocity and direction angle of the wind throughout the one-way voyage in all three seasons in a year, as shown in Table 6-2. Wind data was determined based on studies over around ten years, from September 1999 to October 2009, using the SeaWinds scatterometer. The wind speed and direction data are obtained at 10 meters above sea level. The approximate errors of the model are ± 1.7 m/s and ± 14 degrees for wind speed direction, respectively. [26, 5].

Table 6-2 presents the mean wind speed and direction in three different seasons for the voyage of Marseille- Algeria and Tangier-Southampton. Credits (COGOW) database

Navigation routes	Season	Mean wind speed (V_T)	Mean wind direction angle (β)
		(Knots)	(Deg)
Marseille- Algeria	Mid-season	14	165
	Summer	10.3	157
	Winter	17.5	155
Tangier-Southampton	Mid-season	15	167
	Summer	14	170
	Winter	17	155

6.2.2.5 Environmental Module

In this research, zero-carbon green hydrogen is assumed to be carried in as well as fuel the JAMILA ship, producing a low NO_x gaseous emission only [27]. Environmental descriptions of the modules utilised in this research have been described in detail in reference [22]. The simulation of the ship NO_x emission was evaluated under the impact of COGAS normal condition and degradation at 6% for loaded and unloaded ship conditions. Additionally, the 6 Flettner rotors are assumed to be a renewable energy assistance propulsion system to reduce NO_x emissions. The simulation of the LH2 carrier ship was carried out for three different seasons (mid, summer, and winter)

in terms of COGAS NO_x emission estimation with the ship operation hours for two voyages (Marseille to Algeria) and (Tangier to Southampton).

6.3 Discussions

In this study, the author designed Flettner rotors technology to assist the JAMILA LH2 tanker ship; the new design that included 6 Flettner rotors as a ship assistance clean propulsion system will be shown in the next section. The influence of the 6 Flettner rotors in the COGAS performance and emission was analysed based on engine behaviour for different voyages under loaded and unloaded conditions, normal and 6% degraded engine, and varying ambient conditions to directly compare the prime mover by itself as well as with the assistance of the Flettner rotors as a clean propulsion system. This comparison primarily contributes to the study's techno-environmental assessment outcomes.

6.3.1 New Design Result Description

The LH2 carrier ship design has been developed by adding 6 Flettner rotors on the ship deck. Figure 6-1 shows the new design, which includes 6 Flettner rotors as an assisted propulsion system to achieve high ship performance and low emission targets. The positions of the Flettner rotors onboard the LH2 carrier ship depend on different factors such as the ship size, design, and empty spaces onboard the ship deck. The location of the LH2 tanks offers free onboard ship space to install the Flettner rotors technology considering the optimum space between each rotor. As an expected design result, the additional Flettner rotors positively influence the ship's prime mover efficiency and emission results, details of which are presented in the ship's performance and environmental sections.

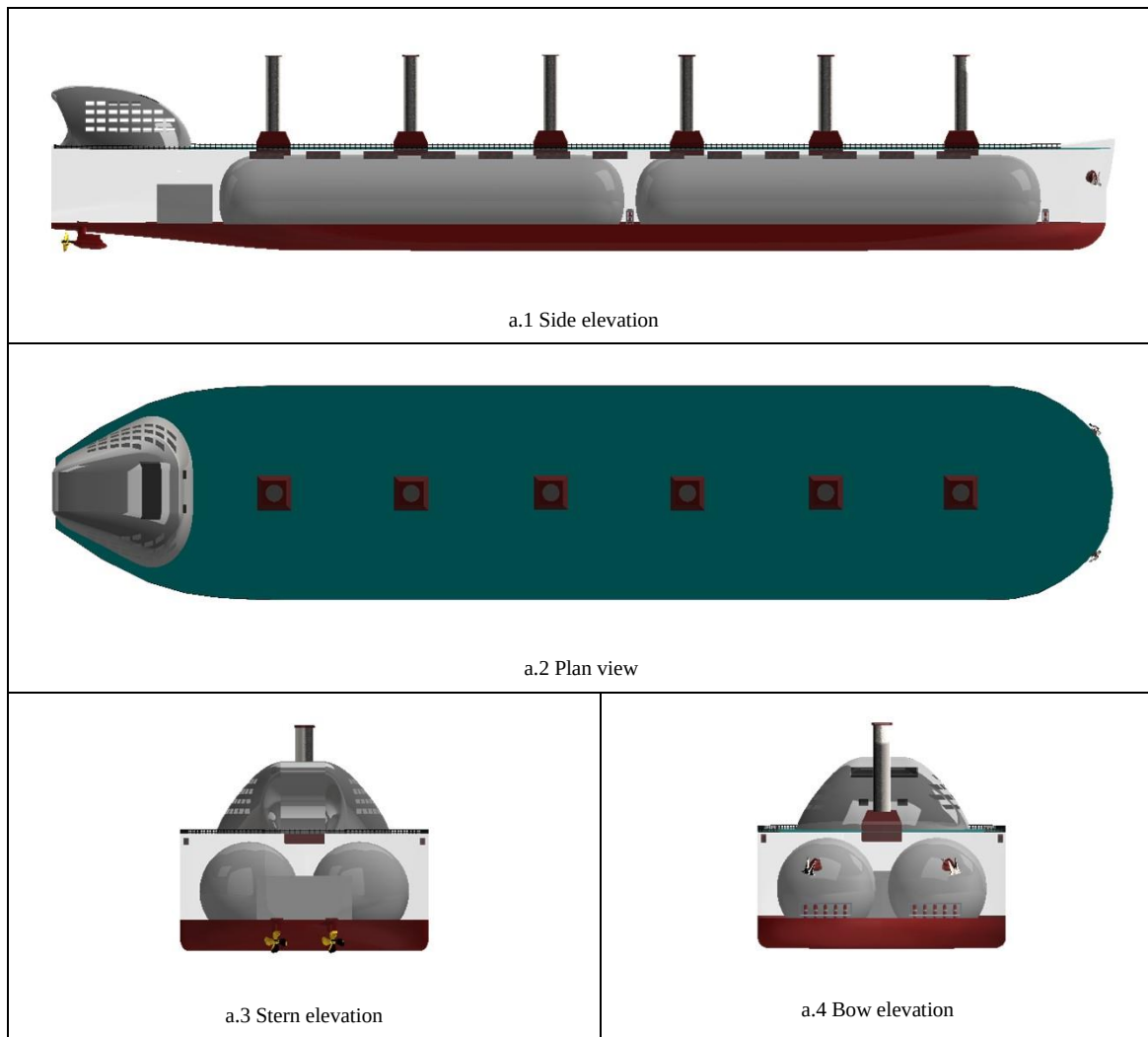


Figure 6-1 JAMILA LH2 tanker ship 3D design including 6 Flettner rotors design; (a1) Side elevation (a2) Plan view; (a3) Stern elevation and, (a4) Bow elevation

6.3.1.1 Ship Performance Analysis

The performance analysis of the liquefied hydrogen tanker ship prime mover in conjunction with a set of 6 Flettner rotors as a wind energy-assisted technology was carried out during two selected voyages. The influence of the Flettner towers in the overall thermal efficiency of COGAS as ship prime mover in off-design conditions was analysed. The LH2 carrier ship voyages propelled by COGAS with enhanced Flettner rotors were simulated from Marseille to Algeria in all three seasons (mid, summer, and winter) in terms of power output and thermal efficiency under the impact of the normal condition and 6% degradation for loaded and unloaded ship conditions. Figure 6-2 shows that the Flettner rotor attained a maximum contribution power range of 1.7 and

1.8 MW in the winter season in both standard and degraded conditions in the case of a loaded and unloaded ship, respectively, owing to the high wind speed and favourable wind direction.

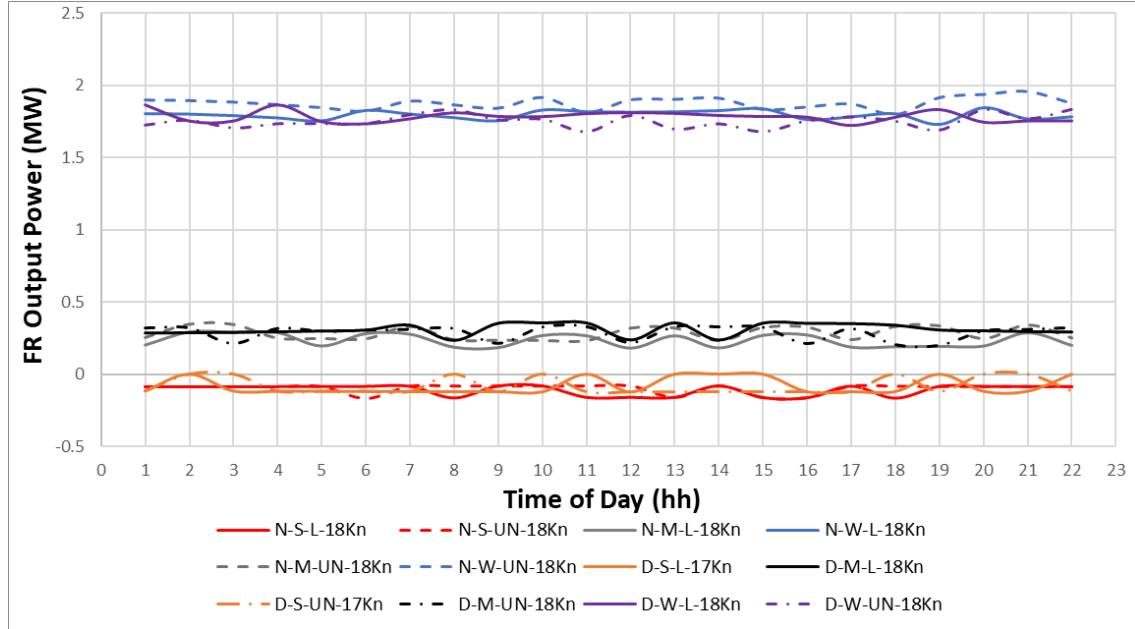


Figure 6-2 Power output in MW of 6 Flettner rotors integrated with COGAS of LH2 tanker ship as a function of voyage time per hour in different conditions (Marseille-Algeria)

Furthermore, in the winter season, the Flettner rotor generated power caused an increase in the COGAS thermal efficiency to 56.5 and 56% in unloaded and loaded conditions, respectively, as shown in Figure 6-3, compared to 55.5 and 55% without installing Flettner rotor [22]. In the case of the degraded condition, the thermal efficiency increased to 55 and 54.7% in unloaded and loaded conditions compared to 54% and 53.7% without Flettner rotor power contribution [22]. On the contrary, in the mid and summer, the Flettner rotor power output was lower than 0.5 MW, while at certain times in summer, negative power, i.e., - 0.2 MW, was realised due to slow wind speed and unfavourable wind direction. Under this condition, the Flettner rotor is creating additional resistance causing additional power requirements for the ship in both loaded and unloaded conditions. Furthermore, in this case, all the Flettner rotors are shut down and acting as an additional wind resistance surface. This resistance causing a negative impact in the ship total output power.

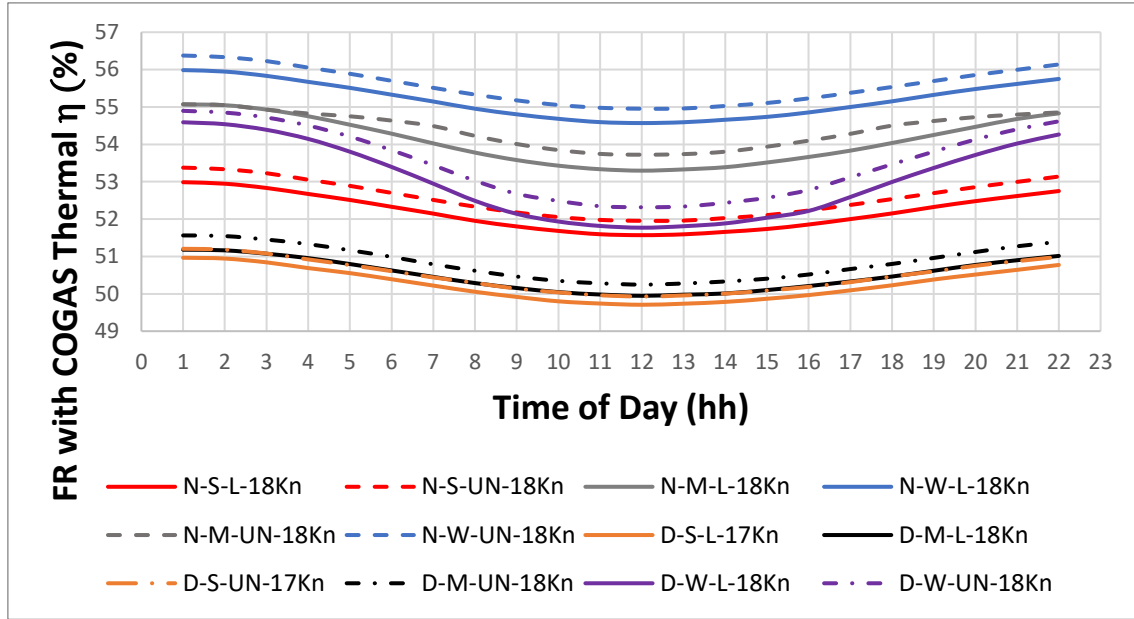


Figure 6-3 The overall thermal efficiency of LH2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Marseille- Algeria)

Similarly, the LH2 tanker ship powered by the integration of COGAS fuelled by hydrogen as a prime mover and 6 Flettner rotors as assistance clean propulsion system was simulated under different conditions from Tangier to Southampton. Figure 6-4 shows that the 6 Flettner rotors maximum outpower contribution in the winter season for Tangier to Southampton voyage is 1.6 MW, lower than the maximum power generated in the Marseille to Algeria voyage; this slight drop in the power is due to lower wind speed influence.

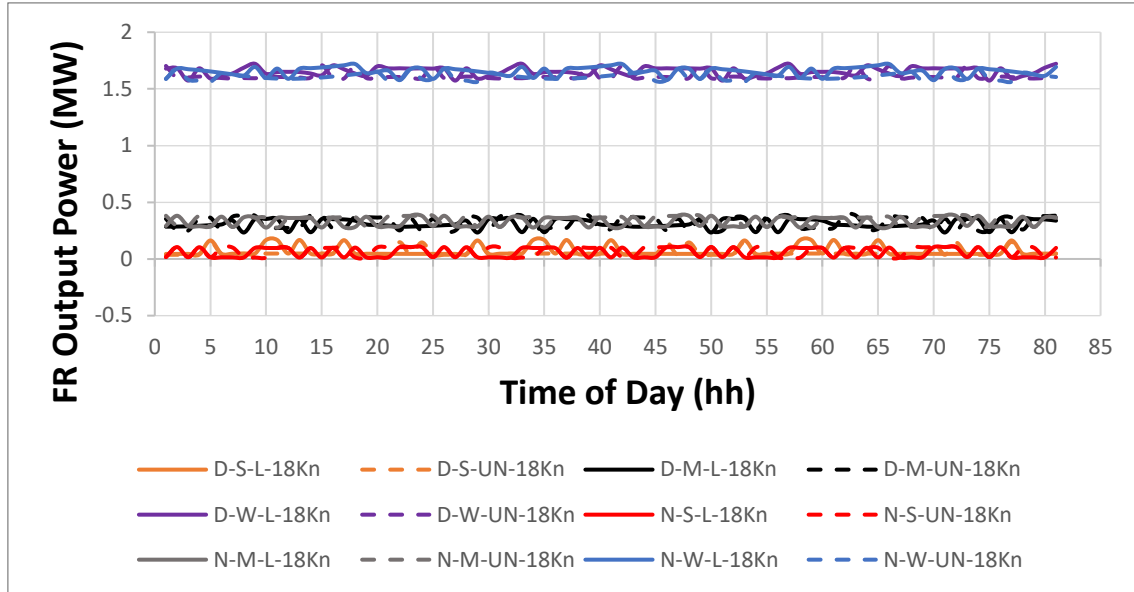


Figure 6-4 Power output in MW of 6 Flettner rotors integrated with COGAS of LH2 tanker ship as a function of voyage time per hour in different conditions (Tangier-Southampton)

Figure 6-5 shows that the maximum efficiency achieved was 55.9% for the normal unloaded condition in the winter season, whereas efficiency of 55% was achieved without installing Flettner rotors technology for the Tangier to Southampton voyage [22]. Considering ship engine degradation of 6% and fully loaded condition for the LH2 tanker, the overall thermal efficiency decreased to a minimum of 49.9% in the summer while it remained at 49.2% for the same voyage without installing Flettner rotors [22].

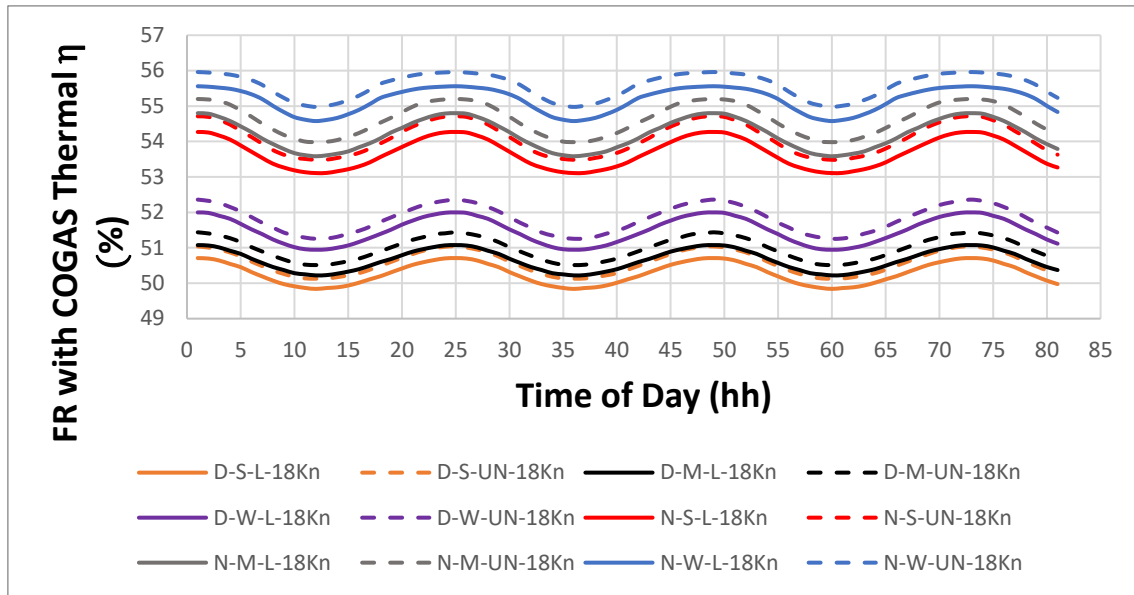


Figure 6-5 The overall thermal efficiency of LH2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Tangier-Southampton)

The wind-energy assisted scenario results demonstrate that the maximum power output from the 6 Flettner rotors decreased by 0.2 MW in the Tangier–Southampton voyage as compared to the Marseille–Algeria voyage. This fall in the power output is due to variation in the wind speed in the winter season; this variation corresponds to 17.5 knots and 155 degrees for the Marseille–Algeria voyage compared to 17 knots and 155 degrees for the Tangier–Southampton voyage. Environmentally, this difference in the power output would slightly impact the LH2 carrier ship prime mover emissions analysis.

6.3.1.2 Emission Analysis Results

The emissions assessment of the LH2 carrier ship propelled by COGAS enhanced with 6 Flettner rotors during two different voyages, viz., Marseille–Algeria voyage and Tangier–Southampton voyage, is described in this section. In this study, the influence of Flettner rotors in terms of NO_x emissions only was considered because zero-carbon green Hydrogen fuel was selected to fuel the COGAS engine. The NO_x emissions of the LH2 carrier ship propelled by COGAS with Flettner rotors were estimated for a one-way voyage from Marseille to Algeria and Tangier to Southampton in different ambient conditions. Figure 6-6 shows the results of the NO_x emission estimation for the

Marseille to Algeria voyage in all the three seasons (mid, summer, and winter) in the engine normal condition and with 6% degradation at loaded and unloaded ship conditions. The results show that the maximum NOx emission amount is 3.4 kg/hr in the mid with a fully loaded ship and at 6% degraded engine for one way 22 hours route. The same figure shows that the minimum NOx emission for the same period is 2.6 kg/hr with the 6% degraded engine at the unloaded condition at a speed of 17 knots.

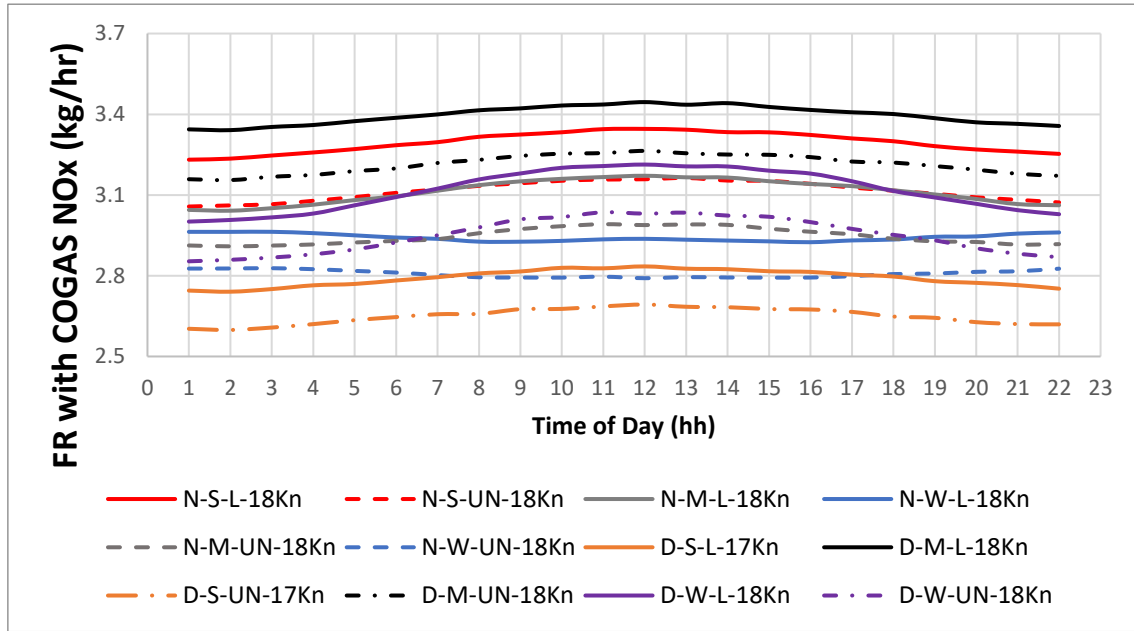


Figure 6-6 NOx emissions for LH2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Marseille- Algeria)

Figure 6-7 shows the NOx emissions for the LH2 tanker ship simulated for the Tangier–Southampton voyage under different conditions. The results show that the maximum NOx emission is 3.5 kg/hr in the summer season in the degraded engine for the fully loaded ship at 18 knots speed, whereas the minimum NOx emission is 2.8 kg/hr in the winter season for an unloaded ship under normal engine condition.

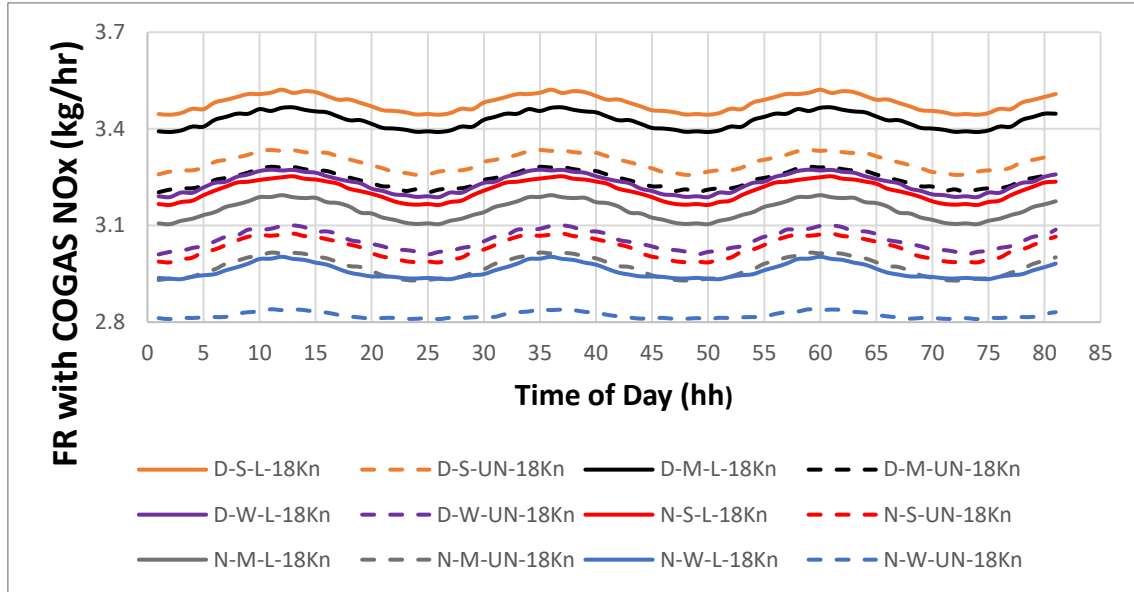


Figure 6-7 NO_x emissions for LH₂ tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Tangier- Southampton)

However, when the NO_x emission of the two voyages after installing the 6 Flettner rotors as an assistance propulsion system was compared, the results show that the maximum NO_x emission decreased by approximately 3% for the Marseille to Algeria voyage in comparison to the Tangier to Southampton voyage. This reduction percentage is due to the increase in the wind speed in the mid-season in comparison to that in the summer season. Conversely, the minimum NO_x emission amount decreased approximately 6% for the Marseille to Algeria voyage in comparison to the Tangier to Southampton voyage. This reduction is due to a reduction in the ship speed from 18 to 17 knots.

6.3.2 Overall Discussion for Techno-Environmental Results

This section offers technical and environmental assessment results by comparing the COGAS fuelled by hydrogen only, which is described in reference [22], with a wind energy-assisted scenario. In both voyages, i.e., Marseille–Algeria and Tangier–Southampton, the results estimate the increase in the COGAS overall maximum thermal efficiency after installing the Flettner rotors as an assistance propulsion system as 1%. Furthermore, the increase in the overall thermal efficiency percentage positively affects the engine NO_x emission in the winter season by decreasing the NO_x emission to approximately 3.4 to 3.5% in comparison with the engine NO_x emission when utilising

COGAS fuelled by hydrogen alone, as shown in Table 6-3. However, the analysis indicates that the utilisation of the Flettner rotors in conjunction with COGAS fuelled by hydrogen produced a more significant benefit in terms of saving fuel, increasing overall thermal efficiency, and decreasing engine NOx emission in comparison with the utilisation of the COGAS as a prime mover of LH2 tanker ship without Flettner rotors as a renewable energy assistance propulsion system [22].

Table 6-3 The influence of the Flettner rotors in the ship engine performance and emissions in different voyages (Marseille- Algeria) and (Tangier- Southampton)

Marseille- Algeria	Maximum engine efficiency (%)	NOx emission in Max engine efficiency (kg/hr)	Case	NOx reduction (%) Compared with B.L. S
COGAS only	55.5% [22]	2.9 [22]	N-W-UN-18Kn	-
Flettner rotor	56.5%	2.8	N-W-UN-18Kn	3.5%
Tangier - Southampton				
COGAS only	55% [22]	2.94 [22]	N-W-UN-18Kn	-
Flettner rotor	56%	2.84	N-W-UN-18Kn	3.4%

6.4 Conclusion

A 280,000 m³ liquefied hydrogen tanker ship with new propulsion system was designed and assessed by applying a techno-environmental method. The assessment covered the performance and environmental advantages that may be achieved by utilising a set of 6 Flettner rotors as renewable energy assistance propulsion system for the combined-cycle hydrogen fuelled gas turbine prime mover of the ship. The influence of the 6 Flettner towers on the behaviour of combined-cycle gas turbine for different voyages, under loaded and unloaded conditions, normal and 6% degraded engine, and varying ambient conditions was analysed in terms of the engine's performance and emission.

Promising results that contribute to the performance enhancement and reduction in overall environmental emissions were obtained; the significant outcomes may be summarised as follows:

- A set of 6 Flettner rotors were designed, simulated, and located on the vessel deck based on the ship size and location of the cargo tanks. Each Flettner rotor

was 40 m in height, 8 m in diameter, with 12 m diameter rotor disc, and had a 6.3 spin ratio. The Flettner rotors functioned as an assistance propulsion system with COGAS to achieve optimum output power from the wind energy technology and increase the propulsion system thermal efficiency by decreasing the prime mover fuel consumption. The results show that the design philosophy of the Flettner towers' installation was significantly dependent on the empty spaces on board the ship deck and the cargo storage locations.

- The hydrogen tanker ship powered by COGAS and assisted by 6 Flettner towers was simulated for two different voyages, viz., Marseille– Algeria and Tangier– Southampton, during three seasons, i.e., mid, summer and winter. The results demonstrate that there is a requirement to decrease the vessel speed from 18 to 17 knots because the ship power required is more than COGAS power output due to the high summer ambient temperature and the 6% degradation influence. The engine degradation and ambient temperature variation play an essential role in the ship's speed.
- The ship propulsion system performance assessment results for both voyages indicated an increase of approximately 1% in the COGAS overall maximum thermal efficiency after implementing the 6 Flettner rotors as an assistance propulsion system. Moreover, the Flettner rotor maximum contribution power achieved was in the range of 1.7 to 1.8 MW in the winter season, owing to the high wind speed and favourable wind direction. This power could save around 3.6% of the combined-cycle gas turbine design output power (50 MW). On the contrary, in mid and summer, the Flettner rotor power output was lower than 0.5 MW, while at certain times in summer, negative power, i.e., - 0.2 MW, was realised due to slow wind speed and unfavourable wind direction.
- The Flettner rotors installation positively impacted engine NO_x emission of the liquefied tanker ship, especially in the winter season. The reduction in the NO_x emission achieved was approximately 3.4 to 3.5% in both voyages in comparison to the COGAS NO_x emission achieved without utilising the set of 6 Flettner rotors as an assistance propulsion system.

The assessment results indicate that the utilisation of the set of 6 Flettner rotors in conjunction with a combined-cycle gas turbine fuelled by hydrogen for JAMILA LH2

tanker ship could contribute substantial benefit in terms of increasing overall thermal efficiency, fuel-saving, and reducing ship prime mover NO_x emission in comparison to the utilisation of the combined-cycle gas turbine as the primary propulsion system of LH2 tanker ship without implementing the Flettner rotors as a renewable energy assistance propulsion technology.

Credit Author Statement

Abdullah NFNR Alkhaledi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software. Suresh Sampath: Supervision. Pericles Pilidis: Supervision.

Declaration of Competing Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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6.5 References

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7 OVERALL DISCUSSION

7.1 Implementation of the Work

The work conducted for this research has demonstrated a novel design of a liquefied hydrogen tanker ship powered by a combined cycle gas turbine fuelled by hydrogen and assessed in terms of technical, economic, and environmental aspects using established methods through five original scientific research papers presented in this thesis to support the future zero-emission objective achievement. A new preliminary design of a 280000 m³ liquefied hydrogen carrier ship was implemented and analysed in terms of the stability to support the global movement to use alternative and sustainable sources of energy in the interest of decarbonisation and enable storage and transportation of liquefied hydrogen, which was published in chapter 2 (Paper. 1). Once the ship hull was designed and evaluated, there was a need to design a novel propulsion system for the ship. Therefore, the propulsion system was designed and evaluated in terms of resistance, power requirements, and power plant performance to complete the LH2 tanker ship design and to achieve the twin objectives of high efficiency and zero-carbon footprint for satisfying global objectives toward climate change, which was published in chapter 3 (Paper. 2). Moreover, the economic feasibility and cost analysis for the LH2 tanker ship was performed to support the realistic applicability of the LH2 tanker ship's completed design and contribute to implementing a green hydrogen economy, which was covered in chapter 4 (paper. 3). To improve the applicability of the suggested design, chapter 5 (Paper. 4) presented an improved design of the LH2 tanker ship simulated in different journeys and conditions to assess the LH2 tanker ship's prime mover using a techno-environmental framework. Moreover, to achieve overall thermal efficiency increasing, fuel-saving and emission decreasing targets for the designed ship prime mover, chapter 6 (Paper. 5) presented an assessment of the performance and environmental impacts of 6 Flettner rotors were installed in the designed LH2 tanker ship as an assistance propulsion system for the combined cycle gas turbine fuelled by hydrogen. In this section, the implementation of the five papers was described, and the work implemented outcomes will be presented as follows:

7.1.1 Overall Design and Technical Analysis Outcomes

The technical results of the LH2 tanker ship design have achieved the expected assessment target. The main technical key findings from the implemented work can be described as follows:

- A comprehensive preliminary design of a 370 m length ship, 75 m breadth, and 10.12 m draft to carry 20,000 tons of liquefied Hydrogen was implemented. The results show that the LH2 tanker ship specifications were unlike other tanker ships such as oil tankers and LNG tankers, especially the ship draft, which is slight compared with other tankers; this result was expected owing to liquid hydrogen properties which are different from other fuel types (a very light and extremally voluminous). (Paper. 1).
- Implementation of 50 MW combined cycle gas and steam turbine model using hydrogen fuel to achieve the twin objectives of high efficiency and eliminate the carbon footprint as a novel propulsion system of liquified hydrogen carrier ship. The results reveal that hydrogen's combined cycle gas turbine is a suitable option as a hydrogen tanker prime mover. Moreover, the output power allows ship operation at a great speed even with a degraded engine and adverse ambient conditions. (Paper. 2).
- The LH2 tanker design was improved and implemented a technical assessment for the design of a liquid hydrogen tanker powered by a hydrogen-fuelled combined-cycle gas turbine (COGAS) as the prime mover by simulating the ship in different journeys and conditions. The results indicated that the single-pressure hydrogen-fuelled COGAS reached a maximum overall thermal efficiency of 55.5%; this percentage is considered excellent compared with the conventional marine prime movers. Furthermore, the technical assessment indicated that the LH2 tanker powered by the hydrogen-fuelled COGAS could successfully achieve an acceptable efficiency target in off-design conditions (Paper. 4).
- A set of 6 Flettner rotors was implemented as an assistance propulsion system in conjunction with a combined-cycle gas turbine fuelled by hydrogen as a prime mover for the LH2 tanker. The maximum power contributed by the 6 Flettner rotors as a renewable energy technology was 1.8 MW; this power could

save approximately 3.6% of the combined-cycle gas turbine total output power (50 MW) and increase the maximum overall thermal efficiency by 56.5%. The results have proven that the Flettner rotor option can be a successful solution in the long term to achieve the sustainability target in the marine sector by improving the prime mover's overall thermal efficiency for hydrogen tankers (Paper. 5).

7.1.2 Economic Assessment Outcomes in General

An economic model was employed to estimate the economic feasibility of the liquefied hydrogen carrier ship in terms of the net present value, internal rate of return, payback period, and economic value-added. The results show that the LH2 tanker ship can cover the capital cost of the ship within six years in the worst-case shipping marine economic conditions. Furthermore, the economic outcomes were found to be promising for the hydrogen economy in the future, which expected a positive impact on the industrial sector. (Paper. 3).

7.1.3 Environmental Evaluation Outcomes

An environmental assessment shows that utilising the hydrogen fuel contributes to limiting the maximum NO_x emission from the LH2 tanker prime mover to 3.5 kg/h. Furthermore, the results indicated that the LH2 tanker powered by the hydrogen-fuelled COGAS could successfully achieve the low emission targets in off-design conditions through different journeys (paper 4). Moreover, implementing a set of 6 Flettner rotors for the LH2 tanker ship as an assistance propulsion system can positively impact the global environment by causing a 3.5% reduction in NO_x emissions (paper 5). However, hydrogen emissions are very low compared with conventional fuels and can achieve an almost zero-emission target in the maritime sector.

7.2 Research Potential Impact

The potential impact of this research can be summarised as follows:

- The proposed design for a hydrogen-carrying ship represents a significant step in the field of ship design. Furthermore, the evolving trends in energy generation

and consumption and the increased focus on hydrogen as a sustainable energy source are expected to enhance the demand for such vessels in the future.

- The future development of sustainable energy systems provides new information that is important for bridging the gap between research, development, and implementation of a green hydrogen economy that will mitigate climate change.
- The research contributes a promising result to reaching the global decarbonisation target.
- The research offers a design of clean technology to achieve the COP26 aims by limiting the global temperature to 1.5 C.
- The project offers a novel hydrogen tanker design to support the hydrogen economy and trade.
- The research impacts ship-owners by providing solutions for reducing shipping emissions and fuel consumption.
- The project will offer researchers a method to design and evaluate LH2 carrier ship propulsion and power systems by modelling alternative technologies.
- The project can support the research of the United Kingdom and the internationally zero-emission plan for the year 2025.
- This research contributes to the ship's industrial sector for the progress meeting of international maritime organisation (IMO) regulations for 2035.
- The project presents a solution for current hydrogen transportation challenges.
- The study supports the nations' objectives and procedures in the process of governing energy transition to achieve the emission reduction targets by 2050.
- The project offers new data for the academic researcher on the scope of renewable energy and hydrogen transportation solutions.

8 CONCLUSIONS

This research contributed an innovative and evaluated novel design of a liquefied hydrogen carrier ship named JAMILA with a total capacity of 280,000 m³ fuelled by hydrogen using state-of-the-art design and analysis methods. The design was implemented and assessed to achieve the almost zero-emission target and the global commitments to mitigate climate change. In addition, an established Techno-Economic Environmental Risk assessment (TERA) framework was developed to assess the designed LH2 tanker ship. While the outcomes found were exceptionally significant, the key point of this research was the design and assessment of an LH2 tanker in various conditions to be a practical solution for transporting a large amount of hydrogen from the production to the consumption hubs. The results of the work can be summarised as follows:

- A preliminary design of a 370 m length ship, 75 m breadth, and 10.12 m draft to carry 20,000 tonnes of liquefied Hydrogen was created. The study indicated that the characteristics of the new design of the LH2 tanker ship are extremely different from the other types of tankers owing to the hydrogen physical properties (a very light but voluminous substance). The study also demonstrated that the difference in LH2 tanker draft between loaded and unloaded conditions is less than 1 meter due to the low density of cargo; this difference was expected compared with other ship designs such as cruise ships and aircraft carriers.
- Four LH₂ tanks of a cylindrical shape capped with hemispheric ends of liquefied hydrogen were designed to be installed in the ship hull using mechanical, thermal and tank liner calculations. The LH₂ tank design results that considered preliminary mechanical sizing, thermal considerations, and liner application investigated and show that the total weight of four LH2 tanks is 87,819 tonnes to carry around 280 000 m³ of liquid hydrogen cargo. In addition, the results show that the tank wall thickness and utilised material type play a key role in the controllability of the tank's weight, which could affect the ship's stability.
- The liquefied hydrogen tanker was examined in terms of stability and passed under IMO criteria to be subject to the 2008 IMO Intact Stability cod (ISC). This

achievement mainly contributed to enhancing the reliability of the suggested LH₂ tanker design.

- A 50 MW combined cycle gas and steam turbine model using hydrogen fuel was implemented as a liquified hydrogen carrier ship propulsion system. The results indicated that the speed limits for the ship power requirements in design and off-design conditions could be between 16 and 18 knots as a minimum and maximum speeds, respectively. This speed plays a crucial role in limiting the LH₂ boil-off from the cargo tanks during the journey.
- A turboelectric system design that includes a combined cycle gas turbine and two azimuthal podded propellers with a maximum power output of 31 MW was implemented as a ship propulsion system. The results showed that the shipping speed, power requirement, and maximum allowable unloaded draft are essential factors in selecting the suitable propulsion system type for the LH₂ tankers.
- The research examined the gas turbine performance in terms of power output and thermal efficiency in the impact of degradation and ambient temperature. The examination results show that the suggested system can be delivered 31 M.W. at a greater than 50% thermal efficiency, allowing a ship speed of 16 knots in the worst-case scenario of high degradation and ambient temperature, which is acceptable, where the ship's maximum requirement power was 49 M.W. for 18 knots in case of fully loaded conditions in calm water. The results proved that a combined cycle gas turbine fuelled by hydrogen could be one of the suitable options for the LH₂ tanker ships.
- The study implemented a systematic economic evaluation to assess the economic feasibility of the suggested LH₂ tanker design through three scenarios. The results indicated that the capital cost of the designed tanker was USD\$480,818,160 which is acceptable compared with the LNG tankers' capital cost. Furthermore, the results indicated a dropping of 58.3 % in the inflow amount in the long-term 2050 scenario compared with other scenarios; this decreased in the inflow owing to the shipping price variability from USD\$1.2 to USD\$0.7/kg. Those results confirmed that the shipping cost plays a critical role in the total yearly income rate of the liquified hydrogen tanker ship. In addition, the outflow value was decreased by around 50.2% in the long-term scenarios;

this reduction is owing to the reduction in the hydrogen price in the long term, which will positively affect the total yearly income amount by decreasing the fuel costs and the liquified hydrogen boil-off from the tanks.

- The designed LH2 tanker payback period (PP) was estimated to be 2.5 and 6 years for the long term in 2040 and 2050, respectively, representing 8.3 % and 20 % of the assumed 30-year operational lifetime of the LH2 tanker. These periods are acceptable and profitable compared to other projects. Therefore, the EVA outcomes proved that the LH2 tanker ship would be a promising and sustainable project for the future.
- A techno-environmental analysis method was developed to simulate a numerical model for a suggested liquified hydrogen tanker design powered by COGAS fuelled by hydrogen as a ship prime mover in different journeys and conditions. The results show that the COGAS achieved the required power at a ship speed of 18 knots in all conditions except in the Marseille–Algeria journey in the summer season with the degraded engine condition; there is a need to decrease the vessel speed to 17 knots because the ship power required is more than COGAS power output. This reduction in power output is due to the high summer ambient temperature and the 6% degradation influence. The results show that the ambient temperature and engine condition were crucial in influencing the ship's speed. In terms of performance impact, the results indicated that the hydrogen-fuelled COGAS could achieve a maximum overall thermal efficiency of 55.5%. The results proved that the ambient temperature, cargo weight, and engine condition are the main factors influencing the ship engine's overall thermal efficiencies.
- Environmentally, the maximum NO_x emissions from the 50-MW hydrogen-fuelled COGAS as a prime mover was 3.5 kg/h at a ship speed of 18 knots. On the other hand, the minimum amount of NO_x emissions was 2.6 kg/h for the same journey at a ship speed of 17 knots. The results indicate that the amount of NO_x emission was significantly influenced by the shipping speed. These results could be an appropriate step for achieving future zero-emission targets.
- The study analysed the utilisation of renewable energy technology as an assistance propulsion system for the ship prime mover by designing, simulating,

and installing a set of 6 Flettner rotors on the designed ship deck. The design results show that the empty spaces onboard the ship deck and the cargo storage locations represented the main factors for the Flettner rotors installation design philosophy.

- A techno environmental method was applied to simulate a set of 6 Flettner rotors as an assistance propulsion system for the combined-cycle hydrogen-fuelled gas turbine prime mover of the LH2 tanker. The results indicated an increase of around 1% in the COGAS overall maximum thermal efficiency after employing the 6 Flettner rotors as an assistance propulsion system. Furthermore, the results indicated that the output power from the 6 Flettner rotors could save around 3.6% of the combined-cycle gas turbine output power in the winter season, owing to the high wind speed and favourable wind direction. On the other hand, the Flettner rotor power output in summer was achieved a - 0.2 MW due to slow wind speed and incorrect wind direction. The results proved that the wind speed and direction are essential in controlling the Flettner rotor's performance.
- Environmentally, the results indicated that the Flettner rotors could be reducing the NOx emission by around 3.4 to 3.5% through both journeys compared to the COGAS NOx emission achieved without utilising the set of 6 Flettner rotors as an assistance propulsion system. The results show that the Flettner rotors could be a successful assistance solution to achieving the maritime zero-emission target.

To conclude, the JAMILA ship design could be a sustainable solution to impact climate change mitigation in the future positively. The results proved that the suggested COGAS fuelled by hydrogen is one of the suitable options for large-scale liquefied hydrogen tankers compared with traditional propulsion systems. The techno-economic and environmental assessment has proven the feasibility of the liquefied hydrogen tankers for the hydrogen economy in the future. Furthermore, the assessment results indicate that the utilisation of renewable energy in conjunction with a combined-cycle gas turbine fuelled by hydrogen for the JAMILA LH2 tanker could contribute significant advantage in terms of increasing overall thermal efficiency, fuel-saving, and reducing ship prime mover NOx emission compared with utilisation of the combined cycle gas turbine alone as a ship prime mover.

9 FURTHER WORK

The current research created and assessed a new design of liquefied hydrogen tankers. However, this research work needs to continue and develop using several related topics represented as follows:

- Design a solar assistance propulsion system for the onboard liquefied hydrogen ship area powered by a combined cycle gas turbine using photovoltaic panels and simulate the new design in different journeys and conditions. In addition, employed a techno environmental framework to assess and compare the performance and emission results with the baseline and wind-assisted scenarios results in this study.
- Implementation of economic analysis to understand the economic feasibility for the liquefied hydrogen tanker in three scenarios, propelled by COGAS fuelled by hydrogen only, in conjunction with Flettner rotors and solar technology through different journeys and conditions.
- Design and evaluate the Flettner rotors' performance by changing the towers' locations and number and comparing it with the current design to achieve the optimum Flettner rotors output power and efficiency.
- Design the combination of COGAS, Flettner rotor, and solar thin films as a power system for liquefied hydrogen carrier ship and evaluate the merge using the Techno-Economic and Environmental risk assessment TERA method, then applying a comparison of the integrated design results with the assessment results of the LH₂ tanker baseline design.
- Implementation of an economic sensitivity analysis model to assess how changes in the assumption of the liquefied hydrogen tanker economic model affect its prediction.
- Employment Nanotechnology to improve the liquefied hydrogen tanks specifications in terms of tanks weight reduction and boil off limitation.
- Design and evaluate a suitable advanced system specifically for the liquefied hydrogen tankers to transfer the boil-off from the cargo tanks to the ship power and propulsion system as zero-carbon fuel.

- Develop an advanced method to decrease the liquefied hydrogen tanker's NO_x emissions by improving the combined cycle gas turbine design and integrating new technologies working towards the maritime zero-emission target.
- Implement artificial intelligence and robotics technology for the liquefied hydrogen tanker's safety system to achieve the optimum level of safety throughout the journeys.
- Design a new hydrogen carrier ship enhanced with a renewable energy system to produce the hydrogen through seawater electrolysis method and store it in the ship tanks to transport a large quantity of hydrogen and support the hydrogen economy blockchain.
- Design and assess novel semiconductors to keep the liquified hydrogen temperature inside the storage tanks at -253C to limit the hydrogen boil-off from the tanks.

APPENDICES

Appendix A

A.1 The Difference Between the Cylindrical and Spherical Tanks

Number of tanks	Vol/tank m3	Radius m	Diameter m	L(total) m
4	70,000	25.56642	51.13284 (Higher than cylindrical)	245.4376
5	56,000	23.73376	47.46753 (Higher than cylindrical)	284.8052
6	46,666.67	22.33433	44.66865 (Higher than cylindrical)	321.6143
7	40,000	21.21569	42.43139 (Higher than cylindrical)	356.4237
8	35000	20.29208	40.58416 (Higher than cylindrical)	389.608

$$V_{spherical} = 4/3 \pi r^3$$

The following reasons to clarify the selection of the cylindrical tank shape rather than spherical:

1. The height of the spherical tanks is more than the ship depth, which is 35 m, increasing ship resistance and stability challenges.
2. The cylindrical tank can be fit inside the ship hull, which offers an empty deck for futuristic utilisation, such as installing renewable energy technology as fuel-saving systems.
3. To decrease the aerodynamic resistance where the intelligent shape of the cylindrical tanks can overcome this challenge.

A.2 Ship and Propulsion System Design Methods

Key finding	Method	Reference
LH2 tank design	Mechanical and thermal sizing, tank liner	- Colozza, A.J., Kohout L., 2002. Hydrogen storage for aircraft applications overview. Technical Report NASA/CR – 2002-211867, Analax Corporation. - Goldberg, C., 2017. Techno-economic, environment and risk analysis of an aircraft concept with turbo-electric distributed propulsion (Doctoral dissertation). - Ishimoto, Y., Voldsund, M., Neksa, P., Roussanaly, S., Berstad, D. and Gardarsdottir, S.O., 2020. Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. <i>International Journal of Hydrogen Energy</i>, 45(58), pp.32865-32883.
Ship hull design	Parents ship (Q-max)	- Lewis, E.V., 1988. Principles of Naval Architecture Second Revision. SNAME, Jersey. - Schneekloth, Herbert, and Volker Bertram. <i>Ship design for efficiency and economy</i>. Vol. 201. Oxford: Butterworth-Heinemann, 1998.
Ship stability analysis	Stability calculation based on IMO intact stability code	- Moore, C.S., 2010. Principles of Naval Architecture Series-Intact Stability. Society of Naval Architects and Marine Engineers. - IMO, 2019. A.749(18) Code on Intact Stability.
Ship Power requirement	Holtrop and Mennen	- Holtrop J, Mennen GGJ. An approximate power prediction method. <i>Int Ship Build Prog</i> 1982;29. - Roh, M.I. and Lee, K.Y., 2018. Computational ship design. Springer Singapore.
Propeller design and azimuthal	B-series	- Oosterveld M, van Oossanen P. Further computer analysed data of the Wageningen B-screw series. <i>Int Ship Build Prog</i> 1975. - ABB. Azipod® XO2100 and XO2300 Product Introduction [online]. 2012
GT model	Turbomatch	- Nikolaidis, T; TURBOMATCH– Gas Turbine Performance 467 Simulation –User Manual, unpublished, Cranfield University 2017. - Luck, D.L., 1998, June. Extending use of marine gas turbines through application of the LM2500+. In <i>Turbo Expo: Power for Land, Sea, and Air</i> (Vol. 78637, p. V002T03A001), American Society of Mechanical Engineers. - Saravanamuttoo, Herbert IH, Gordon Frederick Crichton Rogers, and Henry Cohen. <i>Gas turbine theory</i>. Pearson Education, 2001.
COGAS model	Thermodynamic cycle and Steam tables (MATLAB)	Cengel, Yunus A., and Michael A. Boles. <i>Thermodynamics: An Engineering Approach</i> 6th Edition (SI Units). The McGraw-Hill Companies, Inc., New York, 2007.
Poseidon results	Holtrop and Mennen	- Tsoudis, E., 2008. Techno-economic, environmental and risk analysis of marine gas turbine power plant. PhD thesis, Cranfield University, Cranfield, UK. - Talluri, L., Nalianda, D.K., Kyprianidis, K.G., Nikolaidis, T., Pilidis, P., 2016. Techno economic and environmental assessment of wind assisted marine propulsion systems. <i>Ocean. Eng.</i> 121, 301–311. doi:10.1016/j.oceaneng.2016.05.047.
Whether estimation	Average between two ports	Timeanddate.com

A.3 Outcomes of Examination of The Ship Propeller Performance (Wageningen B-Series) and Investigate the Non-Cavitation Criterion by Using Aufer Keller Formula

Blade Number	Efficiency %
3	54% (Lower efficiency)
4	56% (Pass the cavitation examination)
5	57.8% (Fail the cavitation examination)
6	58.5% (Fail the cavitation examination)
7	58.2% (Fail the cavitation examination)

A.4 The Reason for the Design of the Ship Hull Without Bulbous Bow

The bulb may reduce resistance in the range

$$0.17 \leq F_n \leq 0.7 \quad \text{for} \quad 6\%$$

$$\text{modern bulb } F_n = 0.23 \text{ for } 20\%$$

The Froude number of JAMILA was calculated using the following equation

$$F_n = \frac{V}{\sqrt{g \cdot L_w}}$$

$$F_n = \frac{18 \times 0.5144}{\sqrt{9.81 \times 367.979}} = 0.1541$$

Reference: Schneekluth, Herbert, and Volker Bertram. Ship design for efficiency and economy. Vol. 201. Oxford: Butterworth-Heinemann, 1998.

A.5 The Tanks Boil Off Calculations

$$\text{LH2 fuel required to power the ship} = [SFC \times \text{duration of journey} \times P_{GT}]$$

$$\text{LH2 fuel required to power the ship} = \left[\left(\frac{79.2 \times 1000}{1000000} \right) \times 24 \times 36.2 \right] = 68 \text{ t/day}$$

$$\text{LH2 fuel produced from boil off} = \text{the total mass of hydrogen} \times \text{boil off rate}$$

$$\text{LH2 fuel produced from boil off} = 20000 \times 0.001 = 20 \text{ t/day}$$

$$\text{Fuel saving percentage} = \frac{\text{LH2 fuel produced from boil off}}{\text{LH2 fuel required to power the ship}} \times 100$$

$$\text{Fuel saving percentage} = \frac{20}{68.8} \times 100 = 29\%$$

A.6 Morrish and Munro-Smith Formulas to Estimate Ship Stability

The total displacement of the ship is Δ_{total} , and the transverse moment of inertia is I_T , which is equal to the original moment and the moment of the weight added minus the moment of the weight discharged. The Morrish formula is used for estimating the vertical centre of buoyancy (KB) (Wilson 2018; Roh et al. 2018):

$$KB = \frac{1}{3} \cdot T \left[2.5 - \frac{C_B}{C_W} \right], KB_1 = 4.9 \text{ m (Unloaded)}, KB_2 = 5.3 \text{ m (Loaded)},$$

where the waterplane area coefficients (C_W) in the unloaded and loaded conditions are assumed to be 0.894 and 0.9, respectively, and the corresponding drafts are 9.263 m and 10.012 m, respectively. The metacentric radius (BM) is estimated using the Munro-Smith formula:

$$BM = \frac{I}{\nabla} = \frac{B^2}{T} \cdot \frac{C_W^3}{2C_B(1+C_W)(1+2C_W)}, BM_1 = 50.5 \text{ m (Unloaded)}, BM_2 = 47.0 \text{ m (Loaded)}$$

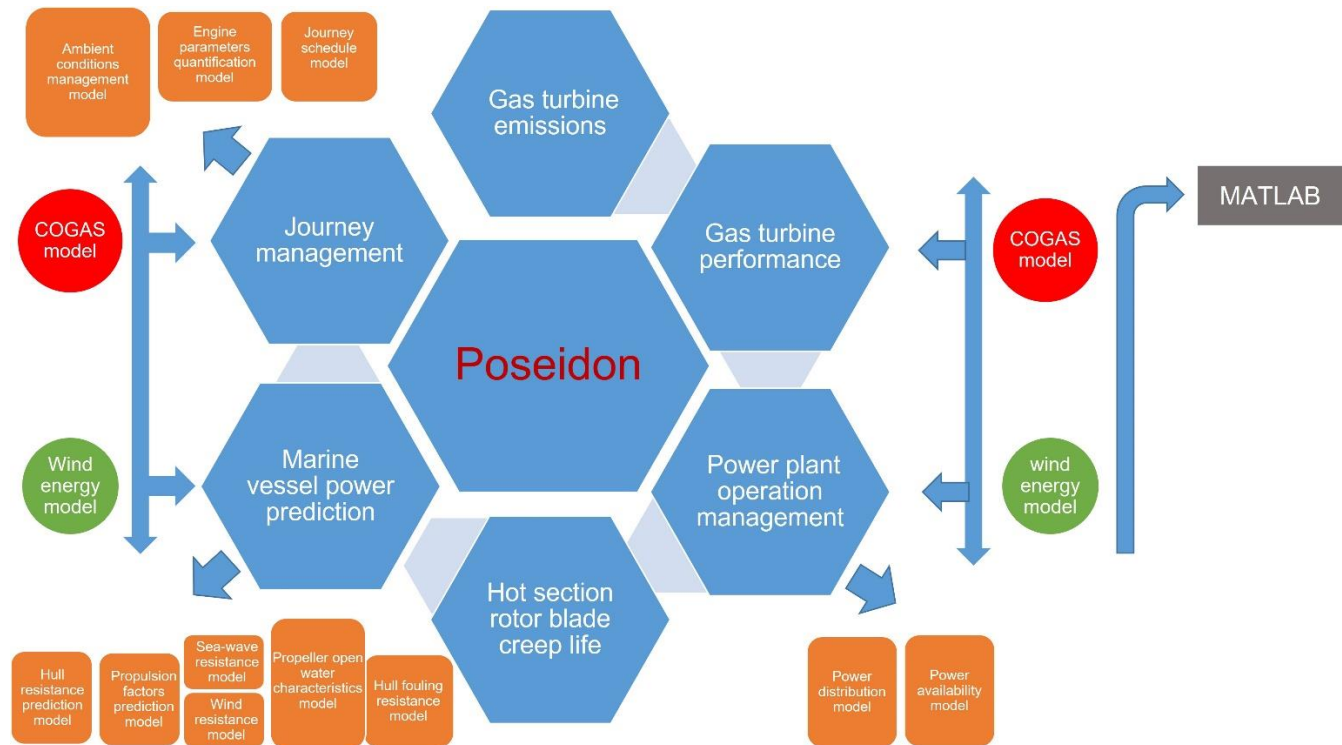
where I is the moment of inertia. The metacentric heights (GM) are

$$GM_{T1} = 4.9 + 50.5 - 16.028 = 39.3 \text{ m (unloaded)},$$

$$GM_{T2} = 5.3 + 47 - 16.054 = 36.2 \text{ m (Loaded)}.$$

Appendix B

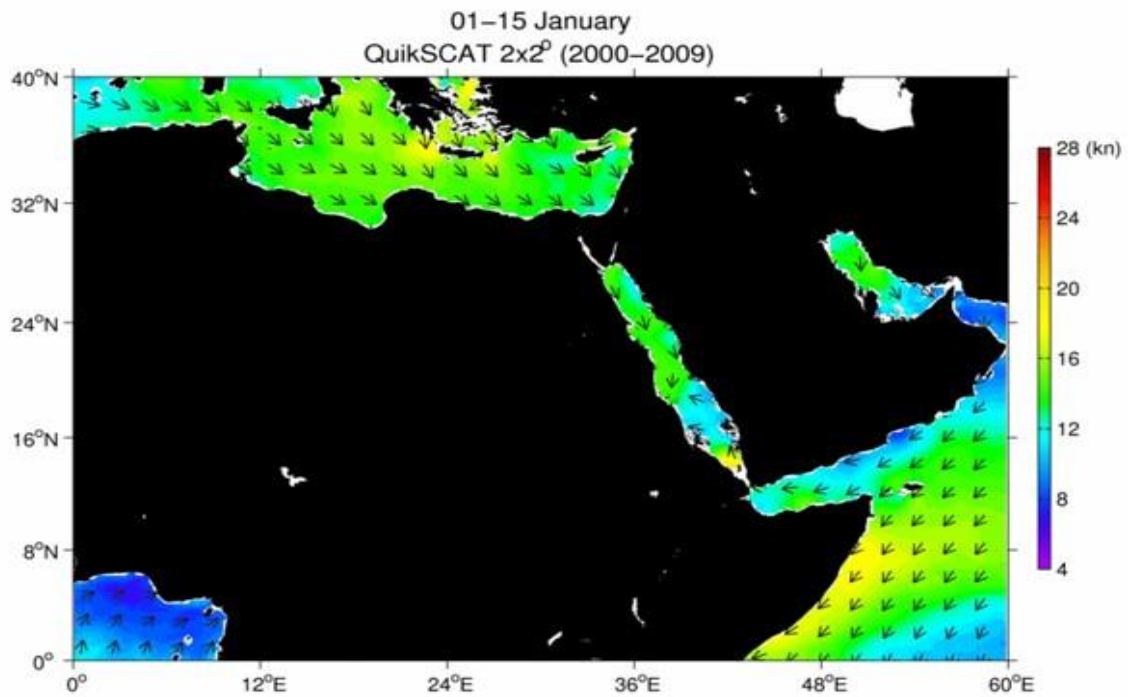
B.1 Poseidon Simulation Tool (Assess Lifecycle and Reliability in Different Journeys and Conditions for the Baseline Scenario)



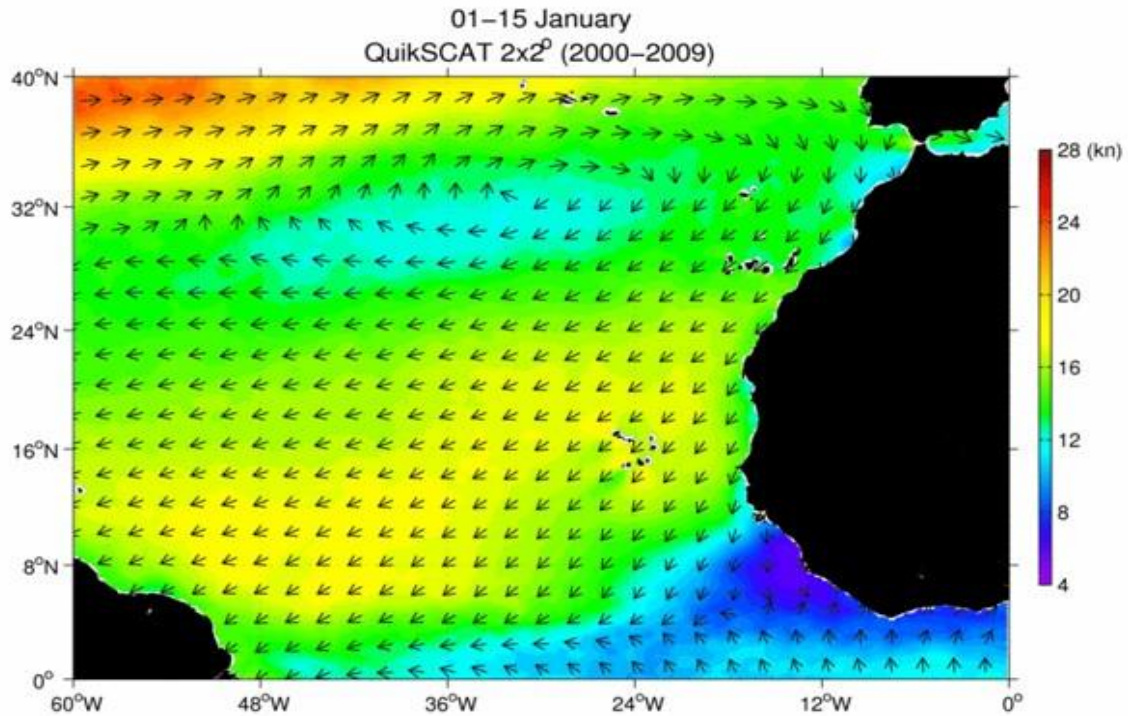
B.2 Flettner Rotor and Techno-Economic and Environmental Risk Assessment (TERA) Methods

Key finding	Method	Reference
Flettner rotor design	1. The lift and drag coefficients that related to spin ratio calculation method 2. The power required to rotate a Flettner tower around its axis estimation method	1. Talluri, L., Nalianda, D.K. and Giuliani, E., 2018. Techno economic and environmental assessment of Flettner rotors for marine propulsion. <i>Ocean engineering</i> , 154, pp.1-15. 2. Tillig, F. and Ringsberg, J.W., 2020. Design, operation and analysis of wind-assisted cargo ships. <i>Ocean Engineering</i> , 211, p.107603. 3. Theodorsen, T., Regier, A., 1944. Experiments on Drag of Revolving Discs, Cylinders and Streamline Rods at High Speeds. NACA Report 793.
Weather routine	Climatology of Global Ocean Winds (COGOW) database	1. Risien, C.M., Chelton, D.B., 2006. "A satellite-derived climatology of global ocean winds <i>Rem. Sens. Environ.</i> 105 (3), 221–236.
Atmospheric module	A method that achievements the utilisation of 3 seasons in the year.	1. Huld, A.T., Sürri, M., Dunlop, D.E., Micale, F., 2006. Estimating average daytime and daily temperature profiles within Europe. <i>Environ. Model. Software</i> 21, 1650–1661.
Aerodynamic resistance	1. Jenes method (a head wind case) 2. Blendermann model (all other cases)	1. Schneekluth, H., Bertram, V., 1998. <i>Ship Design for Efficiency and Economy</i> , second ed. Butterworth-Heinemann, Oxford, UK. 2. Blendermann, W., 1993. Parameter identification of wind loads on ships. <i>J. Wind Eng. Ind. Aerod.</i> 51, 339–351.
Added wave resistance module	1. Gerritsma and Beukelman's method (a head waves) 2. Alexandersson (incident wave angles)	1. Gerritsma, J., Beukelman, W., 1972. Analysis of the Resistance Increase in Waves of a Fast Cargo Ship. Netherlands Ship Research Centre TNO. Report 169S.. 2. Alexandersson, M., 2009. A Study of Methods to Predict Added Resistance in Waves. MSc Thesis. KTH Centre for Naval Architecture, Stockholm.
Environmental model	A method to calculate Emission factor	1. Garaniya, V., 2016. Development of a Methodology to Measure and Assess Ship Emissions, Theme 2-Marine Environmental Issues. 2. Trozzi C. Emission estimate methodology for maritime navigation. 2010; : 6. Available at: http://www.epa.gov/ttnchie1/conference/ei19/session10/trozzi.pdf .
Economic model	Economic model method	1. Alrashed, M., Nikolaidis, T., Pilidis, P., Alrashed, W. and Jafari, S., 2020. Economic and environmental viability assessment of NASA's turboelectric distribution propulsion. <i>Energy Reports</i> , 6, pp.1685-1695. 2. Talluri, L., Nalianda, D.K. and Giuliani, E., 2018. Techno economic and environmental assessment of Flettner rotors for marine propulsion. <i>Ocean engineering</i> , 154, pp.1-15.

B.3 COGOW Satellite (Wind Speed and Angle)



Marseille-Algeria



Tangier-Southampton

Reference: http://cioss.coas.oregonstate.edu/cogow/0101/55_one_x_one.html.